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An attempt of characterization of stress state in high carbon C68D steel wire rod by Barkhausen noise method

***Abstract**. The paper presents preliminary tests of high carbon steel wire rods by the non-destructive Barkhausen method. Correlation between applied external stress to the wire rod and current sweep characteristics were observed. Some geometrical parameters of the shape of these characteristics corresponded to mechanical stress state were assigned. Obtained result can be used for more reliable estimation of residual stress state and quick comparison of residual stress level in wire rod after different production variants.*

***Streszczenie.** W artykule zaprezentowano wstępne badania walcówki ze stali wysokowęglowej za pomocą nieniszczącej metody Barkhausena. Zaobserwowano korelację pomiędzy zadawanymi w walcówce naprężeniami a charakterystykami typu sweep. Pewne parametry geometryczne kształtu tych charakterystyk, korespondujące ze stanem naprężeń mechanicznych, zostały wyznaczone . Uzyskane rezultaty mogą być pomocne dla bardziej wiarygodnej oceny stanu naprężeń własnych i szybkiego porównywania ich poziomów w walcówce po różnych wariantach produkcji (**Próba oceny stanu naprężeń w walcówce zestali wysokowęglowej C68D za pomocą metody Barkhausena**).*

Keywords: wire rod, non-destructive testing, Barkhausen noise.
Słowa kluczowe: walcówka, badania nieniszczące, szum Barkhausena

Introduction

The high carbon steel wire rods are used in areas when high strength and wear resistance are required, for example, in machine building, or automotive or wire-drawing industries. The increase of quality requirements and the optimization of production and further processing of wire rod imply research in this area [1, 2]. Obligatory tests of functional properties of wire rods, according to the standards, cover microstructure investigations and mechanical tests

Complement and enrich these studies can provide various non-destructive (NDT) testing which let to examine wide part of material without time-consuming samples preparation. From a point of view of material strength, the postproduction residual stress level have a great influence on mechanical properties [3, 4]. It may be reason of unexpected plastic deformation and finally, reduce the fatigue strength of the exploited element made from the wire rods. For quick evaluation of residual stress, beside of ultrasound or portable X-ray systems [5], the wide group of magnetic methods has growth potential [6, 7].

Especially, method based on magnetic Barkhuasen noise (MBN) measurement, under millimetres resolution and measurement depth about hundreds of micrometers, between XRD and ultrasonic method is positioning. Being investigated sub-surface layer is especially important due to crack initiation in this area. Invaluable are also short time of measurement or possibility of in-line measurement.

Generally, the MBN method relies on the well-known fact of abrupt motion of the Bloch walls between pinning sites in ferromagnetic materials during magnetization process, discovered by Barkhausen in 1919. Microscopic discontinuous changes in magnetic flux density, results as characteristic noise in the form of voltage pulses (corresponding to Barkhausen jumps of domain's walls) induced in a coil placed or surrounding material. Detailed course of this phenomenon is determined by a lot of parameters as: microstructure type, grain size or number of dislocations, establishing the energetically favourable domain structure [8]. Beside of influence of these material properties, the stress dependence of Barkhausen effect is well recognized. In steels, with positive magnetostriction, tensile stress increases MBN intensity but compressive decreases it. The most sensitive parameters to the stress are energetic as root mean square value of MBN or number of Barkhausen peaks [6]. Moreover, magnetization conditions as field strength and its slew rate have great impact on Barkhausen effect, too [9].

Typical method of residual stress testing, involves on comparison of measured in the tested material selected MBN parameter, with calibration characteristic prepared for the same parameter in function of applied external stress [10]. In case of investigations of wires or the wire rods, obtaining of calibration sample does not pose rather significant problem as for massive, single, or unique product [11, 12]. But the significant problem occurs with preparation of the non-stress state in the specimen. Usually necessary operation of its straightening not only does not remove the residual stress, but causes rebuilding and constitution of new stress state and introduces plastic deformation. Moreover, the heat treatment as annealing of the specimen does not always provide full stress relaxation without microstructure changing. The same, the results of residual stress measurement can be affected by considerable error and discussable if they are based on the no fully relaxed calibration sample or with no adequate microstructure [13].

Considering the above facts and limitations of traditional approach to the BN method, seems to be right to search of measurement techniques, which can give general information about stress state without needing laborious calibration. In [14] authors of this work, as the research method, the alternative approach to BN method applied, when the relative shape of so-called magnetization current sweep function (1), was used as an indicator of residual stress character and their level in massive hot rolled ring.

$$MBN = f(I_m)\big|_{\sigma} \tag{1}$$

where: MBN – current density, I_m – magnetization current, σ – given stress level in sample or material.

According to the study [9], if tensile stress reaches higher value in the material, curve (1) takes more characteristically sigmoidal shape, with a bigger slope rate and characteristic knee as well as the appearance of plateau (saturation) at higher values of magnetization. Analogously, flattening of the curve (1) is correlated with compressive stress occurrence.

Similarly, concept of application of the MBN sweep function, but for case depth verification of hardening, was described in [15].

In the present study, the effect of tensile and compressive stress on sweep function (1) in high carbon content steel wire rods was studied in laboratory conditions. On the basis of obtained results, the basic parameters, initially characterizing the shape of these curves were assigned. By comparison parameters of sweep functions, sample rods from different variants of their production process can be quickly compared under the terms of appearing of the residual stress.

Material and research method

The material investigated in this study, was Ø5,5 mm wire rod made of high carbon steel type C68D (code 1.0613) with yield stress R_e about 600 MPa, used for production wires and ropes. Chemical composition (in wt%) of this steel, according to EN10016-2 standard was: C – 0,68, Si - 0,18, Mn – 0,65, Ni – 0,06, P – 0,011, S – 0,015, Cr – 0,05, Mo – 0,013, Al – 0,004, Cu – 0,11.
The properties of this steel can be representative also for other grades with similar high carbon content e.g. as C70D or C72D.

For the test, the 420 mm centimetres long, arc-shaped samples, were cut off from batch of the wire rod circles. The wire rod was in as-delivery state and had typical pearlitic structure with bainite (Fig.1). To avoid rebuilding of the after-production constituted residual stress state in subsurface layer, straightening operation or surface preparation were not applied to the specimens.

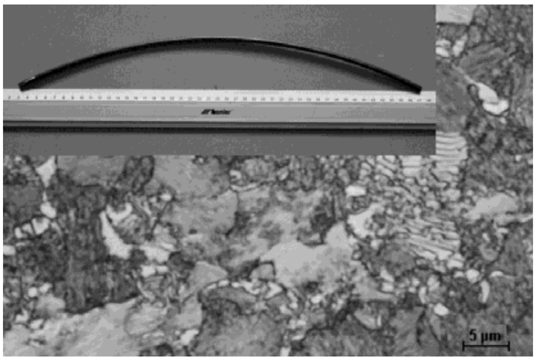

Fig.1 View of tested specimen and its microstructure.

The magnetic Barkhausen noise measurement and examinations were carried out using the stand-alone measurement equipment for excitation, detection and processing of MBN developed by author [16]. The functional diagram was shown in Figure 2. It consists of three main parts: a magnetization block, a Barkhausen noise measuring circuit and signal processing block. Moreover, the measuring head that integrates both function of material magnetization and Barkhausen jumps pick-up, is integral part of it.

The magnetization unit is based on the symmetric saw tooth generator (1) and a current power amplifier (2). It provides current I_m, feeding the magnetization windings (3) wounded on yoke (4) of measuring head. Six predefined frequency: 1, 3, 6, 12, 22 and 38 Hz can be chosen and the amplitude of the current can be regulated in range 0 …±1,5A. The MBN signal generated in the tested specimen (5), is picked by a detection coil (6), placed between yoke poles and transmitted to the measuring block. At first, raw signal is amplified with help of specialized low-noise measuring preamplifier (7) with controlled gain k_{u1max} up to 80 dB. Then, the signal is passed through a high-pass filter (8) with cut-off frequency of 1 kHz, where power line interferences and magnetization current components (8) are eliminated. Finally, extracted from the background MBN, is gained additionally by second amplifier (9) with k_{u2max} = 40 dB and fed to a processing block.

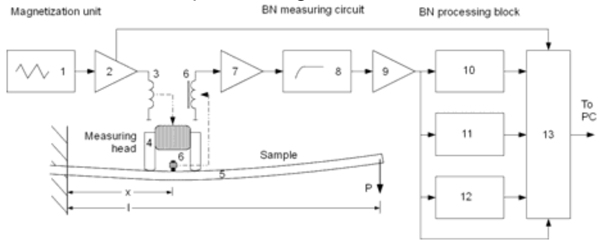

Fig.2 Schematic view of experimental set-up (see text for description)

Processing in specialized circuits involved the MBN root mean square value (MBN_{RMS}) deriving (10) and its envelope voltage signal shaping (11). Moreover, digital pulses correspond to the Barkhausen jumps with amplitude over specific reference voltage are created (12) These signals as well as pure MBN and the magnetization current in form of voltage signal are acquired by data acquisition card (13) type DAQ3000 1 MHz and sent to the computer via USB interface for further processing, saving and displaying. For the tests, a compact measuring head was used constructed on the base of C-shape core. The poles of the yoke were rounded faintly to obtain repeatable contact conditions with different curvature radius of tested wire rods. The magnetization windings had 400 turns. Between the electromagnet poles, the detection coil was fixed elastically in a way enabling its movement. It had 200 turns wounded on ferrite rod core with cross section ~ 5 mm^2. The whole structure was placed inside rectangular aluminium housing.

The studies of relationship between longitudinal stress and MBN_{RMS} vs magnetization current I_m producing family of current sweep functions (1) were performed. One of the endings of the specimen was fixed permanently and the second was loaded by a force to bending and generate tensile or compressive stresses on the rod surface. Considering the fact that the sample may be assumed as slightly curved rod, one-axial, longitudinal stress value σ_l on the surface of the wire rod can be approximated from simplified model for straight bar, by formula (2)

$$\sigma_l = \frac{4P(l-x)}{\pi r3} \qquad (2)$$

where: P – applied force, l – length of sample, x – distance of measuring head from fix point, r – radius of wire rod.

The force by the dead load system was applied. Single step load of 0,5 kg suspended at the extremity of the wire rod produced force P about 5N that generated stress σ_l ~115 MPa, in location where the detection coil touches the material. The loads were applied incrementally causing full elastic strain state initially and then, start of plastic deformation. In view of the significance of tensile stress which can occurs during unrolling or straightening and initialize creep and crack, the MBN measurements during experiment were carried out only on the inner side of arc of the wire rod.

At first, the tension stresses were induced, in configuration shown in Fig.3. To each applied load, a set of MBN measurements were performed. It included, for given frequency of the magnetization f_m = 6 Hz, series of 11 measurements of MBN parameters taken at magnetization current I_m varied between 0 and ~800 mA and registered on computer with a measuring period of 1 s.

After initializing plastic deformation, indicated generally by decreasing of MBN, the sample was rotated horizontally and vertically and analogical compressive cycle was applied. The operation of reversal the sample was dictated by the need for elimination of influence of plastic deformation effects on MBN [17].

Results and discussion

Figure 3 show the example oscillograms of the Barkhausen noise, when the +110 MPa of tensile stresses was applied to the sample. The magnetization current amplitude was ~0,7 A. The result for the same magnetization condition, but for -110 MPa of compressive stresses applied was shown in Fig. 4. Generated in the tested material signal, was typical to the pearlite structure waveform which envelope were reported e.g. by [18]. Observing both of waveforms, although the two peaks on MBN were not clearly visible, it can be concluded that the stress significantly affect rather the first part of Barkhausen signal, which was produced by ferrite component [19].

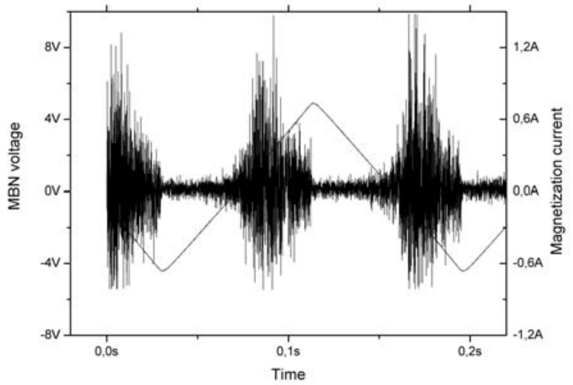

Fig. 3 Sample oscillogram of Barkahausen noise at +110 MPa tensile stress applied

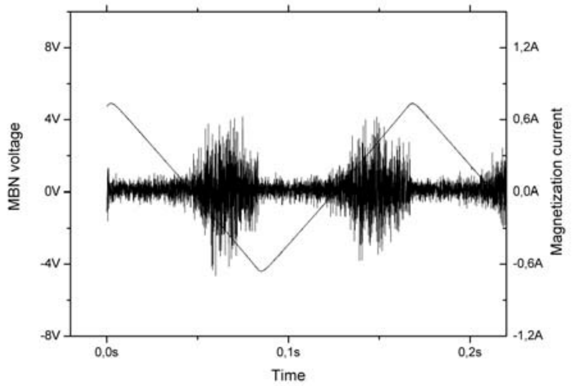

Fig. 4 Sample oscillogram of Barkahausen noise at -110 MPa compressive stress applied.

Figure 5 shown the variation of MBN_{RMS} with magnetization current I_m (given in arbitrary unit) and applied external tensile stress from 0 (σ_0) to 460 MPa (+σ_4) in elastic strain range. The solid lines through the data points represent the fit of the model, currently being developed by the author, to the experimental results. First, observed in this curves family effect is that root mean square value of MBN increases with tension stress growth at each value of I_m. This fact is generally well known and recognized on experimental and theoretical way [20].

The next loads, not shown on plots, which generated respectively 575 MPa and 680 MPa, near and beyond of R_e of tested material, caused plastic deformation manifested by decrease of MBN_{RMS} but this phenomenon was not analyzed in this paper.

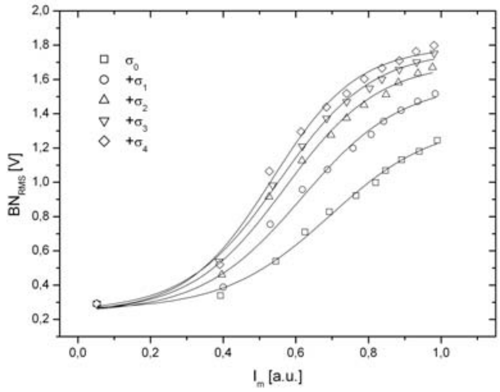

Fig.5 Variation of MBN_{RMS} signal with magnetization current I_m at various values of applied tensile stress σ

Similar, analogical results were obtained when compression stresses in the same range 0 (σ_0) to 460 MPa (-σ_4) were induced to the sample. In this case, as shown in Figure 6, compressive stress causes decreasing of MBN_{RMS}. A little difference between courses of both characteristic at σ_0, results from a change of measurement point during tension and compression.

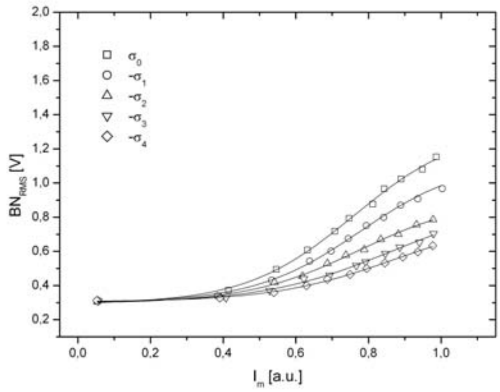

Fig.6 Variation of MBN_{RMS} signal with magnetization current I_m at various values of applied compressive stress σ

At given magnetization, dependence $MBN_{RMS} = f(\sigma)$ creates classical calibration characteristic, which can be used for stress evaluation [10]. But due to mentioned uncertainties associated with the determination the 0 MPa point of such characteristic, in case of the sample was not fully relaxed or material's microstructure changes, the right estimation, even only the character of the residual stress, can be problematic [11].

Next noticed effect, which is proposed for improvement of stress estimation by MBN method, relies on characteristic (1) shape modification under stress. If tension stresses increase, slope ratio of linear part of transition section increase too and appearance of characteristic knee was observed (Fig.6). In contrast, compressive stress growth was indicated by the curve flattening and slope ratio decreasing. Generally, in whole elastic range, if stress becomes large, (in sense of monotonic migration from σ-→ σ+.) these changes are smoothly. It is consistent with previous reports of author [9, 14]

At this point, should be concluded that in sense of the changes in shape of sweep functions (1), these curves correspond to the results of behaviour's investigation and modelling of magnetic hysteresis loop in function of applied stress, reported in [6, 20].

To describe quantitatively obtained results, two parameters of sweep functions (1) were determined: the hypothetical saturation level of MBN_{RMS} saturation towards the magnetization k_{sat} and slope ratio k_a of transition section. These coefficients will be also used in future works for construction complex mathematical model for residual stress estimation on the base of family sweep functions. The values of these parameters were summarized in Table 1 for the tensile and in Table 2 for compressive stress

Table 1 Values of coefficients k_a and k_{sat} for tensile stress

	Applied tensile stress [MPa]				
	0	+115	+230	+345	+460
k_a	1,26	1,63	1,88	1,98	2,20
k_{sat}	1,35	1,58	1,70	1,77	1,79

Table 2 Values of coefficients k_a and k_{sat} for compressive stress

	Applied tensile stress [MPa]				
	0	-115	-230	-345	-460
k_a	1,33	1,07	0,91	0,90	0,80
k_{sat}	1,15	0,95	0,67	0,57	0,49

In both cases, the differences between the values of coefficient k_a are noticeable, and in the range of -230MPa to 230 MPa, in principle, it changes linearly. Beyond this range, curve of changes k_a with σ slightly moves towards saturations and its both halves indicate on homothety through point: (0MPa, 1,3V). In addition, analyzing the changes of the second designated factor k_{sat} in function of stress; it essentially describes the typical calibration function.

Taking into consideration “symmetry” of changes of designated coefficients and lack of clear visible knees on the sweep curves in no external load state (at σ_0), presented in Figure 5 and Figure 6, it may be assumed that in the investigated section of high carbon wire rod, no significant tensile residual stress level on inner surface was disclosed. Work is currently under way to examine residual stress by alternative, portable X-ray or destructive methods, to confirm obtained by MBN measurement results.

Summary

The objective of this study was an attempt to characterize the residual stress state in high carbon C68D steel wire by alternative approach to classical Barkhausen method. A strong correlation between shape of current sweep function (1) and longitudinal stresses was found and a few known MBN dependences reported for other types of steel were confirmed too.

By evaluation the shape of the sweep function, for example, the sample rods from different variants of production process can be characterized and quickly compared under the terms of appearing of the residual stress. In studied arc of wire rod, seems not to be presence of considerable residual stress, however, more work needs to be done to verify obtained results by other methods. Further work will be also concentrated on building complex model of function (1) including influence of plastic deformation.

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