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MEASUREMENTS OF THE MECHANICAL BARKHAUSEN NOISE IN FERROMAGNETIC STEELS

ABSTRACT *This paper presents a new technique for measuring the mechanical Barkhausen noise in ferromagnetic steels. We study the effect of tempering time of P91 grade steels on: parameters of mechanical Barkhausen noise, mechanical hardness and magnetic coercivity. All of these quantities are compared. The variations in amplitude of root mean square of mechanical Barkhausen noise for different tempering times are revealed to be greater than those of hardness and coercivity.*

Keywords: *mechanical Barkhausen noise, ferromagnetic steels, NDT, nondestructive testing, tempering*

1. INTRODUCTION

Mechanical Barkhausen noise signal consists of series of voltage pulses induced in the detecting coil close to the surface of the ferromagnetic specimen,

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with non-zero magnetostriction, when specimen is dynamically loaded with stress. Stress acts on the magnetic domain structure in the material forcing the non-180° magnetic domain walls (DW) to move. Structural defects such as dislocation tangles, precipitates and grain boundaries anchor DW until sufficient stress is applied. This results in an abrupt movement of DW that leads to series of rapid changes of internal magnetization. These changes can be detected as voltage pulses in a coil surrounding or adjacent to the specimen. This induced voltage signal provides information about DW activity under varying external stress level. It was stated that internal stress distribution function can be evaluated by means of mechanical Barkhausen noise [1, 2]. The integral of mechanical Barkhausen noise intensity over one period of oscillation was also postulated to be proportional to mechanical energy losses owing to magneto-mechanical hysteresis process. In this paper we present a new method of measuring mechanical Barkhausen noise for bar like samples and we apply this method for investigation of mechanical Barkhausen noise properties of tempered martensite ferromagnetic steels (TMFS).

Magnetic domain configuration in a demagnetized sample is the configuration that has the lowest energy. This energy level is affected by mechanical properties of the material through the magnetoelastic energy component. The first loading of a demagnetized sample hence yields the information about the magneto-mechanical properties of a material. Since local magnetization in ferromagnetic material with nonzero magnetostriction is induced by the mechanical loading, decreasing oscillations of load demagnetize the sample.

Magnetic Barkhausen noise (MBN) technique is a proven and sensitive non-destructive testing (NDT) method for external stress evaluation and thermal treatment characterization of ferromagnetic materials. The evaluation of external stress in TMFS using the MBN technique requires one to estimate the tempering state of the examined sample in order to achieve the highest accuracy [3], as the MBN is strongly influenced by both the thermal treatment and internal stress. This estimation can be done by examining mechanical hardness (HV), magnetic coercivity (H_c) or, as we suggest, using the mechanical Barkhausen noise. Martensitic transformation causes the formation of dislocations in the material and, in turn, increases DW pinning forces. Tempering of TMFS is reported to decrease the dislocation density, even by a factor of 10 for longer tempering times [4], which reduces the pinning forces of stress barriers formed around dislocations. These structural changes should impact the mechanical Barkhausen noise intensity. It is assumed that mechanical Barkhausen noise decreases with the increase of dislocation density. Because of this feature we propose mechanical Barkhausen noise as a new, sensitive indicator of evolution of dislocation density, mainly when tempering process is applied.

2. MATERIALS AND METHODOLOGY

We used P91-grade steel samples cut, from the thick-walled pipe, to the following dimensions: length (140 \pm 1) mm, width (11 \pm 0.5) mm, thickness (5 \pm 0.5) mm. Six samples were austenitized at a temperature of 1050 $^{\circ}$ C for a period of one hour and then air quenched. Five samples, austenitized and quenched, were tempered at a temperature of 750 $^{\circ}$ C, each for a different time (15, 30, 60, 120 and 240 minutes) and air cooled.

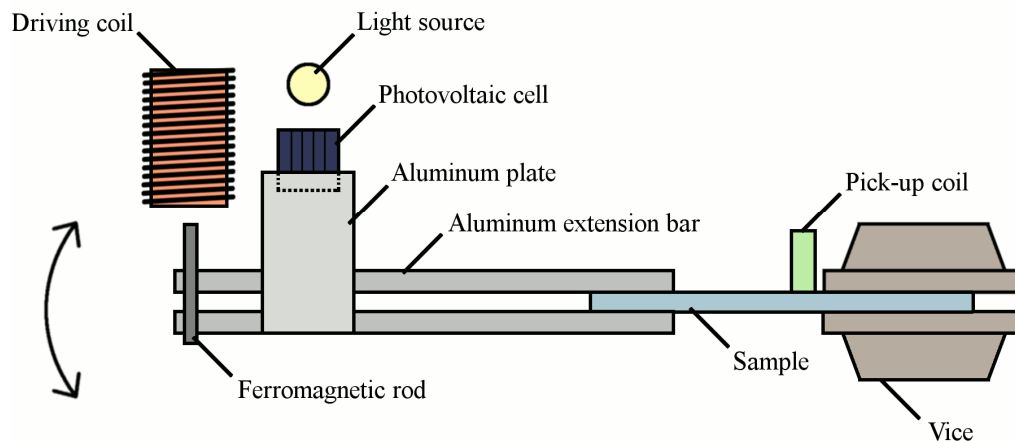


Fig. 1. Schematic of the free-vibrating bar apparatus

Apparatus used in this experiment was built at the Faculty of Applied Physics and Mathematics of Technical University of Gdansk. Figure 1 presents mechanical Barkhausen noise measurement experimental setup. Samples were stress-loaded using the free vibrating bar technique. The examined sample was attached to stiff extension bars on one end with the other end held in a vice. The vibrating part of the sample was 55 mm in length. Battery of capacitors discharging through a driving coil provided initial excitation of vibrations, generating a short (\sim 20 ms), strong electromagnetic force on the ferromagnetic bolt mounted on the free end of extension bars. The use of capacitors allowed for a high repeatability of excitations. During this experiment the strain level in the examined sample was always below the elastic limit.

The mechanical Barkhausen noise signal was detected using a pick-up coil attached perpendicular to the sample surface near the vice. This coil consisted of 2000 turns of copper wire, 0.072 mm in diameter wrapped over nylon casing and was shielded with SiFe wrapping. Ferrite core of 3 mm diameter was also used. The induced mechanical Barkhausen noise voltage signal was amplified and filtered before root mean square (RMS) of the said signal,

U_m , was calculated as a descriptor of mechanical Barkhausen noise intensity. Vibrations were detected using a screened photocell method. Plate attached to the extension bars screened half of the photocell illuminated by halogen bulb. Current in the photocell circuit was used as a signal source for estimation of surface strain of the sample. Amplitude of this current is proportional to the amplitude of strain. Both the strain-proportional and the MBS RMS voltages were acquired using a fast DAQ board.

The mechanical Barkhausen noise intensity, measured as an RMS value, is affected by the rate of the stress applied to the specimen. The higher the stress rate, the more Barkhausen jumps occur at the same time which results in higher number of voltage pulses in the detecting coil and a higher RMS value. Strain rate varies during different stages of oscillation, which results in a variously attenuated RMS signal, depending on the rate and amplitude of oscillations. We used single excitation to initialize the oscillations. Therefore to obtain the real strain dependency of mechanical Barkhausen noise intensity, signal U_m must be corrected for strain rate.

The output signal of mechanical Barkhausen noise meter has a noise level of RMS amplitude $U_b \approx 30$ mV. It has originated mainly from the electromagnetic waves produced by the laboratory equipment surrounding the mechanical Barkhausen noise pick-up coil. To find the "real" mechanical Barkhausen noise signal level, this noise level was subtracted from the total signal U_m using the formula:

$$U_c = \sqrt{U_m^2 - U_b^2}, \quad (1)$$

where U_c is the filtered RMS mechanical Barkhausen noise voltage, U_m is the measured RMS mechanical Barkhausen noise voltage, U_b is the environmental noise RMS voltage. All of the results of mechanical Barkhausen noise intensity presented have been filtered using the above formula, unless stated otherwise.

The strain rate dependency of mechanical Barkhausen noise intensity is assumed to be linear, as it was found in [5] to be roughly linear. It should be noted that in the cited experiment increasing material fatigue affected the results. The strain rate-corrected mechanical Barkhausen noise intensity signal U is given by the equation:

$$U = \frac{U_c}{\frac{\partial \varepsilon}{\partial t}}, \quad (2)$$

where U_c is the filtered RMS of the mechanical Barkhausen noise voltage signal and ε is strain (in arbitrary units).

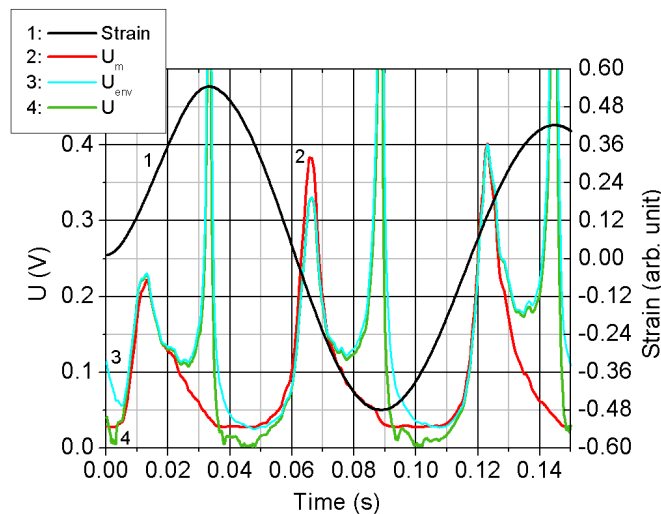


Fig 2. Time dependence of surface strain ε (plot 1), RMS (unfiltered) of mechanical Barkhausen noise U_m (plot 2), strain rate-corrected mechanical Barkhausen noise intensity for the unfiltered (U_{env} , plot 3) and filtered (U , plot 4) signal. Plots shown are for the first 1.5 oscillations for the sample tempered at a temperature of 750°C for a period of 120 min

An example of mechanical Barkhausen noise signal and its analysis is shown in Figure 2. The main signals are: the strain signal (Figure 2. plot 1) and the unfiltered RMS of the mechanical Barkhausen noise (Figure 2. plot 2), both plotted against time. One can see that due to the correction procedure in the vicinity of strain peaks the level of corrected signal of mechanical Barkhausen noise is very high. This is because of the very low strain rate, which is the division factor in equation (2). That does not pose a problem for oscillations with amplitude high enough, because the mechanical Barkhausen noise peaks appear in the unaffected area. It is also visible that due to the great number of turns in the search coil and proper shielding, the signal-to-noise ratio is high and the noise filtering procedure (unfiltered, strain-corrected signal is shown in Figure 2. plot 3 and filtered, strain-corrected signal is shown in Figure 2. plot 4) is not necessary in this case, as it does not affect peak size, shape and position.

3. RESULTS AND DISCUSSION

First parts of mechanical Barkhausen noise intensity (U) loops plotted as a function of strain are shown in Figure 3. The mechanical Barkhausen noise signal was strain-corrected after environmental noise was subtracted as explained in section 2. Because of the correction procedure, at the beginning of the plot and in the range of maximum strain, very high levels of U appear. This is why the initial points of all of the plots were skipped. The level of U increases and the maximum mechanical Barkhausen noise activity peak appears at lower

strain values, for samples tempered for longer times. However, this is not true for the sample tempered for a period of 240 minutes: although the peak appears at a lower strain level than for the previous sample, its level is evidently lower. Mechanical Barkhausen noise maximums for the first two samples (tempered for 15 and 30 minutes) are not yet detectable due to the too low strain amplitude and thus only a change of slope, related to this peak, may be seen. It should be noted that the rapidly increasing part of the plots 1 and 3 (Figure 3) is due to the correction procedure. This is seen for strain levels higher than 0.4 and for plot 2 for strain above 0.35, respectively.

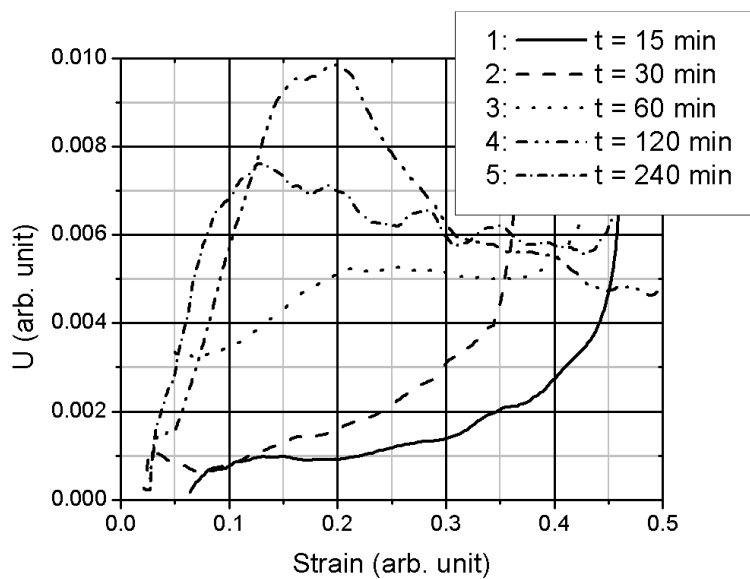


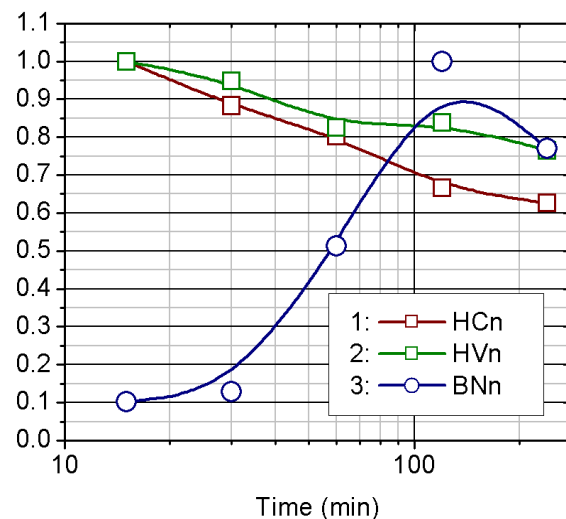
Fig. 3. First load part of loops of mechanical Barkhausen noise strain-corrected signal for samples tempered at a temperature $T = 750^{\circ}\text{C}$ for various tempering times t

To compare sensitivities of H_c , HV and mechanical Barkhausen noise intensity amplitude to tempering time, all of these dependencies were normalized to their highest values. These dependencies are plotted in Figure 4. In this case the highest mechanical Barkhausen noise amplitude of U_m in the first oscillation was taken as a reference value for mechanical Barkhausen noise signal. U_m reaches a maximum for tempering time of 120 minutes and then decreases. Both H_c and HV decrease with increased tempering time but with different intensities. H_c decreases down to about 60% of H_c and HV decreases down to about 75% of HV of the value measured for the sample tempered for 15 minutes. U_m increases from a level of 10% of its maximal value. It is evident that U_m (figure 4 plot 3) varies with a much higher rate than H_c and HV .

It is known that mechanical Barkhausen noise is associated with the movement of DW and that its intensity is affected by the number of pinning sites as well as their pinning forces. Dislocation tangles generate local internal stress fields which pin DW (generating pinning sites) until external stress allows to unpin DW. As it was mentioned in section 1, the mechanical Barkhausen noise

RMS signal during the first loading may be associated with the internal stress distribution function. We assume that the peak of the first loading mechanical Barkhausen noise curves, shown in Figure 3, corresponds to the pinning force of most of the pinning sites. It is known that the tempering of TMFS reduces the number of dislocations. This may lead to the weakening of the DW pinning forces and to the decreased emission of mechanical Barkhausen noise at higher stress levels. That should be seen as the mechanical Barkhausen noise peak shifting towards lower strain levels. This is true for all of the samples, as it is shown in Figure 3. Lower dislocation density affects both the mechanical hardness and the magnetic coercivity, as it is shown in Figure 4.

Fig. 4. Material properties as functions of tempering time: HCn normalized H_c , HVn – normalized HV, BNn – normalized U_m maximum level in the first oscillation. All quantities were normalized to their maximal values



4. CONCLUSIONS

Comparison of mechanical Barkhausen noise, H_c and HV sensitivities to tempering time revealed that U_m amplitude of mechanical Barkhausen noise intensity is subjected to almost two times greater changes than the values of the two other quantities. It was found that with increasing tempering time the mechanical Barkhausen noise intensity peak occurs at lower strain levels, which denotes that the internal stress level around dislocation tangles was reduced.

A new method for measuring and evaluating mechanical Barkhausen noise intensity was presented, which, as examined, may allow the determination of tempering state of P91-grade steel with higher accuracy than the hardness and coercivity measurements. We argue that mechanical Barkhausen noise signal level strain distribution is more sensitive to tempering time than mechanical hardness or magnetic coercivity.

LITERATURE

1. Augustyniak B., Degauque J.: New approach to hysteresis process investigation using mechanical and magnetic Barkhausen effects, Journ. of Magn. and Magn. Mater. 140-144, 1837-1838, 1995.
2. Augustyniak B., Degauque J.: Microstructure inspection by means of the mechanical Barkhausen effect analysis, J. de Phys. 6, C8-527-C8-530, 1996.
3. Augustyniak B., Maciakowski P., Piotrowski L., Chmielewski M., Łabanowski J.: Charakterystyki naprężeniowe stali, X20, Energetyka 21, 1-5, 2010.
4. Pešička J., Kužel R., Dronhofer A., Eggeler G.: The evolution of dislocation density during heat treatment and creep of tempered martensite ferritic steels, Acta Mater. 51, 4847-4862, 2003.
5. Sultan M., Kleber X., Chicois J., Vincent A.: Mechanical Barkhausen noise during fatigue of iron, NDT&E International 39, 493-498, 2006.

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WPŁYW OBRÓBKI CIEPLNEJ
NA WŁAŚCIWOŚCI MECHANICZNEGO
EFEKTU BARKHAUSENA W STALI P91

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STRESZCZENIE *W pracy została opisana metoda badania mechanicznego efektu Barkhausena z wykorzystaniem drgań giętnych belki. Badany był wpływ czasu wygrzewania hartowanej stali P91 na: właściwości mechanicznego efektu Barkhausena, twardość mechaniczną oraz pole koercji. Stwierdzono, że amplituda obwiedni sygnału napięciowego mechanicznego efektu Barkhausena wzrasta wraz z czasem wygrzewania, natomiast twardość mechaniczna oraz pole koercji maleją. Natężenie mechanicznego efektu Barkhausena wykazuje największą dynamikę względnych zmian, co pokazuje, że jest to najczulsze narzędzie do oceny stanu wygrzewania stali P91.*

Słowa kluczowe: *mechaniczny efekt Barkhausena, stale ferromagnetyczne, badania nieniszczące, obróbka cieplna stali*