# MAGNETIC NONDESTRUCTIVE TESTING OF PLASTICALLY DEFORMED MILD STEEL

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**Summary** The Barkhausen noise analysis and coercive field measurement have been used as magnetic nondestructive testing methods for plastically deformed high quality carbon steel specimens. The strain dependence of root mean square value and power spectrum of the Barkhausen noise and the coercive field are explained in terms of the dislocation density. The specimens have been subjected to different magnetizing frequencies to show the overlapping nature of the Barkhausen noise. The results are discussed in the context of usage of magnetic nondestructive testing to evaluate the plastic deformation of high quality carbon steel products.

## 1. INTRODUCTION

Nondestructive testing (NDT) has gained in importance as a result of the rapid technological progress during the past half-century in areas such as aviation and nuclear energy, in which there are high risks, and strict precautions are required. The preliminary investigations are necessary to predict any likelihood of the occurrence of structural changes and the appearance of defects, which may lead to possible failure [1]. Several techniques are now available for testing materials for structural changes, such as X-ray, low angle neutron diffraction and magnetic techniques. Magnetic methods of NDT of metallic (magnetic) materials belong to the most used, mainly from the viewpoint of simplicity and thus the cost. Magnetic measurements, especially Barkhausen emission measurements, show excellent sensitivity to residual stress levels and changes in microstructure of material. Barkhausen noise arises from the discontinuous changes in magnetization process as a result of discontinuous motion of domain walls, domain nucleation and annihilation, and irreversible rotation of magnetization [2-3]. These irreversible changes of magnetization can be detected by sensing coil as a high frequency stochastic signal. The nature of the detected signal is influenced by external factors such as stress, fatigue as a result of cyclic loading, short-term overloading or loading at elevated temperature. All of these types of degeneration processes can be roughly modeled as certain state of plastic deformation. The presented paper investigates influence of increasing plastic deformation of samples of low-carbon steel (12 014). The prepared samples with different state of plastic deformation were tested by Barkhausen method and simultaneously the traditional hysteresis parameter (coercivity) was recorded.

## 2. THEORY

Most metal materials are deformed elastically only to the strain of about $5.10^{-3}$. At the greater deformation the stress-strain curve is not linear and the permanent or plastic deformation arises. The physical principle of plastic deformation results from the disturbance of atom bonds and creating new ones by moving atoms to the new positions in the crystal lattice. The position of this disturbance in the crystal lattice is called dislocation. After removing the mechanical stress the atoms don't return to the original positions, but remains at new ones.

The dislocation density rises with plastic deformation. These dislocations act as hindrances to domain wall motion and thereby influence the Barkhausen noise. The individual Barkhausen jumps accomplished after releasing a domain wall from a hindrance tend to cluster and create large Barkhausen jumps [4-5]. The power spectrum of this noise provides information about correlation of individual jumps. When the magnetization frequency if sufficiently small and the average number of individual jumps in large Barkhausen jump $\rho >> 1$, then the power spectrum of Barkhausen noise $S(\omega)$ is [4]

$$S(\omega) = S_i(\omega)\left(\frac{2\rho}{(\tau\rho\omega)^2 + 1}\right), \tag{1}$$

where $S_i(\omega)$ is the power spectrum of individual jumps and $\tau$ is the average time between individual pulses. At low frequencies the power spectrum of Barkhausen noise reduces to $S(\omega) \cong 2S_i(\omega)\rho$. Plastic deformation changes the average number of individual pulses $\rho$ in large Barkhausen jump due to the change of the dislocation density in the sample and also other factors, for example bending and changing number of domain walls in the sample.

## 3. EXPERIMENT

Four cylindrical rods of the low-carbon steel (Behanit, C<0.06, Mn<0.45, Si<0.15, P<0.02, S<0.02, Al<0.02) with initial (before loading) diameter 13.4 mm were plastically deformed by mechanical tension. The tensile strains after unloading were 0.93, 2.2, 4.3 and 6.3 %. Computer control of loading machine preserved constant rate of strain $\varepsilon$. The loading diagrams of prepared rod samples are shown in Fig. 1. The samples for measurement of Barkhausen signal and coercivity were then cut by water-beam from rods in shapes of closed rings with cross-section of about 5 mm$^2$.

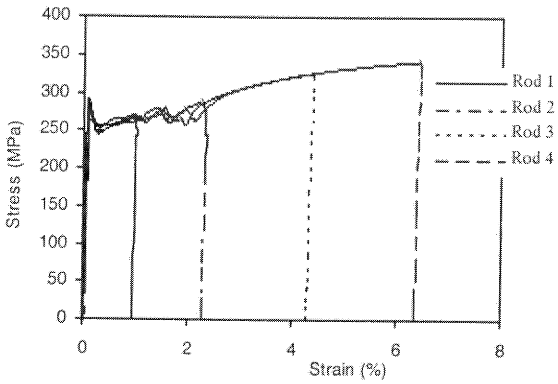


*Fig. 1. Stress-strain curves of plastically deformed samples with $d\varepsilon/dt = 1.24\times 10^{-4}\ s^{-1}$.*

A schematic diagram of the hardware configuration of the Barkhausen noise measurement system is shown in Fig. 2. Magnetizing coil $N_1$ (outer) with 50 turns is wound around whole perimeter of the ring and inner pick-up coil $N_2$ with 100 turns registers the induced

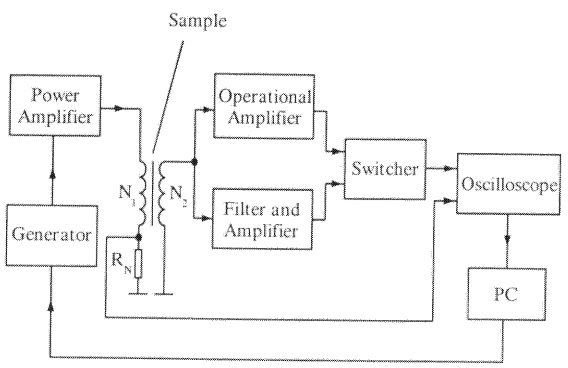


*Fig. 2. The system for measuring the Barkhausen noise and hysteresis parameters.*

voltage. The measured sample is then core of the unloaded transformer. It is excited by a signal from the arbitrary waveform generator Agilent 33120A amplified by the power amplifier and led to the primary (magnetizing) winding of the transformer. The power amplifier realized with OPA544 can provide maximum voltage 30 V and maximum current 2 A. LC filter used to remove quantization noise of the generator is placed at the output of the power amplifier.

The magnetic field intensity $H(t)$ in the sample is according to Ampere's law

$$H(t) = \frac{i_1(t)N_1}{l_m} = \frac{u_{RN}(t)N_1}{R_N l_m} , \tag{2}$$

where $i_1(t)$ is the primary current, $N_1$ the number of turns of the primary winding, $l_m$ the magnetic path length and $u_{RN}$ the voltage on the sensing resistor $R_N$.

The magnetic flux density $B(t)$ in the sample can be determined from the secondary voltage $u_2(t)$ according to Faraday's law

$$B(t) = \frac{1}{N_2 A}\int u_2(t)\,dt , \tag{3}$$

where $N_2$ is the number of secondary (pick-up) turns and $A$ is the cross-section of the core. The voltage from the secondary winding is led through the operational amplifier and the low noise preamplifier with the band-pass filter SR560 to two inputs of the electronic switch. The band-pass filter with cut-off frequencies 1 and 30 kHz filters the Barkhausen signal. The Barkhausen signal or the entire amplified secondary voltage and the voltage from sensing resistor $R_N$ are led to 2-channel oscilloscope LT342. The oscilloscope and arbitrary waveform generator are connected to the personal computer PC through GPIB bus. The controlling program written in VEE programming environment reads these voltages from the oscilloscope and displays the hysteresis loop and the Barkhausen signal. The coercivity is calculated from the hysteresis loop and the spectrum and root mean square value is evaluated from the Barkhausen noise.

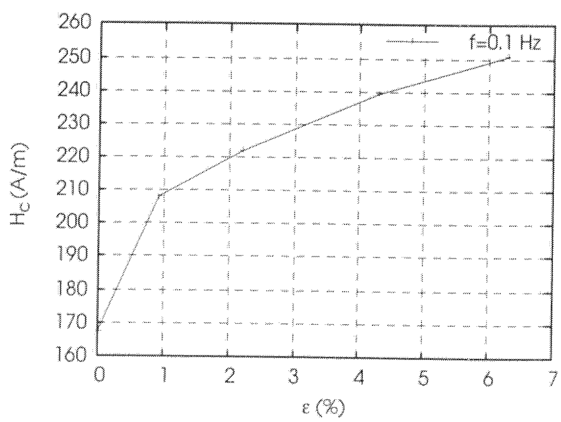


*Fig. 3. The dependence of the coercivity $H_c$ on the plastic strain $\varepsilon$ at the magnetizing frequency 0.1 Hz.*

Our samples were magnetized by a triangular waveform magnetic field with different frequencies and constant maximum field intensity $H_m$=1.2 kA/m ($B_m \cong 1.65$ T at $\varepsilon = 0$). Figure 3 shows the influence of the plastic strain on the coercivity for the magnetizing frequency 0.1 Hz. The dislocations in samples act as pinning sites and hinder the motion of domain walls. Vicena made the first attempt to calculate the magnetic field intensity necessary to separate a plane 180° domain wall from dislocations parallel to the wall surface [6]. Seeger and Trauble [7] calculated the coercive field using a statistical distribution of dislocations. Both models lead to the conclusion that the coercivity

$$H_c = \left[ \sum_i^n \left( \frac{1}{n} H_{wi} \right)^2 \right]^{1/2} = const \times N_d^{\;1/2} \quad , \qquad (4)$$

where $H_{wi}$ is critical pinning field of individual domain wall and $N_d$ is dislocation density. When the plastic strain rises, the dislocation density increases and the pinning becomes stronger. This causes the increase of coercivity according to the equation (4).

The measured power spectrum of the Barkhausen noise in the samples for the magnetizing frequency 0.1 Hz is shown in Fig. 4. The maximum value of the power spectrum increases with plastic deformation because of increasing the average number of individual Barkhausen jumps $\rho$ due to rising dislocation density. This dependence of the deformation on the spectrum is highly influenced by the type of the measured material

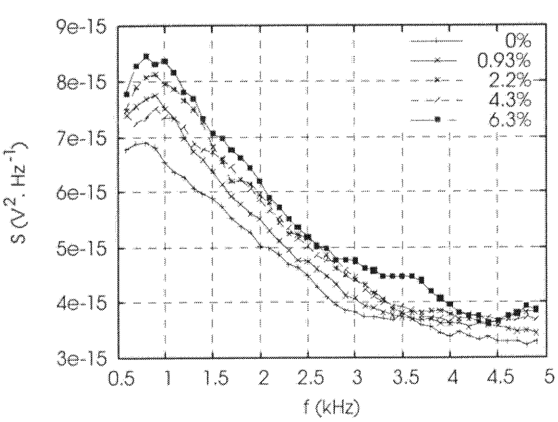


*Fig. 4. Influence of the plastic strain on the power spectrum of the Barkhausen noise at the magnetizing frequency 0.1 Hz.*

and its microstructure and also by measuring conditions. Actually in some cases the change of the spectrum with plastic strain can be very different [4].

The cut-off frequency of the power spectrum increases with plastic deformation, too. The increase of Barkhausen noise with deformation is also illustrated in Fig. 5, which shows the dependence of the root mean square value on plastic strain.

The spectrum of the Barkhausen noise also changes with the magnetizing frequency because of overlapping the independent pulses at different positions in the sample [5]. Figure 6 shows the dependence of the power spectrum on magnetizing frequency at the strain 6.3%. The increasing magnetizing frequency at constant maximum field intensity causes the increasing the number of pulses per unit time and therefore raising the influence of overlapping. So the maximum value of the power spectrum increases with the magnetizing

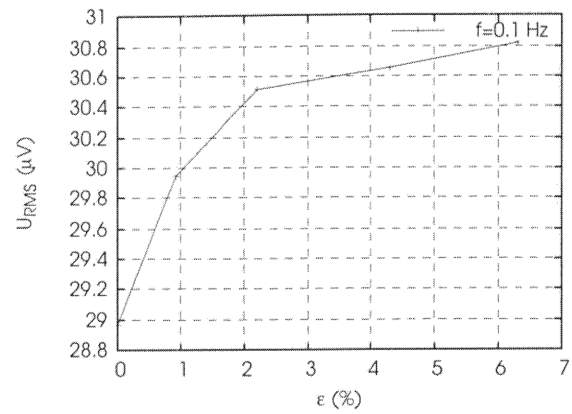


*Fig. 5. Influence of the plastic strain $\varepsilon$ on the root mean square value $U_{RMS}$ of the Barkhausen noise at the magnetizing frequency 0.1 Hz.*

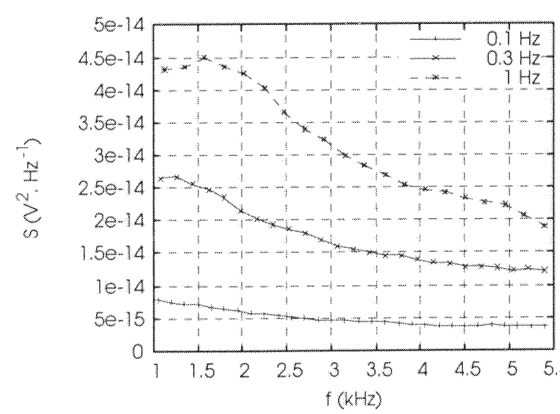


*Fig. 6. The power spectrum of the Barkhausen signal for the 6.3% strained sample at the magnetizing frequencies 0.1, 0.3 and 1 Hz.*

frequency. Moreover, the increase of the magnetizing frequency decreases the time between individual Barkhausen jumps $\tau$ and therefore the cut-off frequency of the power spectrum increases. It follows from this that the increasing the magnetizing frequency can enlarge the magnitude of the Barkhausen signal. However, large magnetizing frequency causes the decreasing the change of the Barkhausen signal with plastic strain and therefore also the sensitivity of the measured parameters on the plastic strain. On the other hand, small magnetizing frequencies require the usage of the acquisition system with the capability to store large amount of data in one period of the magnetizing signal to get also high frequency components of the Barkhausen signal. Further, the Barkhausen signal is small in this case and it is very disturbed by the spurious noise. Thus optimal magnetizing frequency for this measuring system is about 0.1 Hz at the maximum field intensity $H_m$=1.2 kA/m.

## 4. CONCLUSION

The Barkhausen noise analysis and classical measurement of hysteresis parameter $H_c$ (coercivity) were performed to investigate the influence of plastic deformation of low-carbon mild steel. The increase in root mean square value of the Barkhausen noise and coercivity at plastic strain range up to 6% is due to dislocation multiplication, with effect of saturation for high dislocation density. Both the coercivity and the power spectrum of the Barkhausen signal are influenced by the rate of magnetization process. The increasing magnetizing frequency causes the increasing the number of Barkhausen jumps (stochastic induced voltage pulses) per unit time and therefore raising the overlapping. The maximum value of the power spectrum increases, but the change of the Barkhausen signal with plastic strain decreases. Small rate of magnetization requires the usage of the acquisition system with high signal to noise ratio and capability to store large amount of data in one period of magnetizing cycle. The measurement of the coercivity is advantageous from the aspect of high sensitivity of about 50% at magnetizing frequency $f = 0.1$ Hz.

**Acknowledgement**

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## REFERENCES

[1] Blitz J., Electrical and Magnetic Methods of Nondestructive Testing, Adam Hilger IOP Publishing, Bristol (1991)

[2] Matzkanin G. A., Beissner R. E. and Teller C. M., NTIAC Report No. 79-2, SRI, San Antonio (1979)

[3] Jiles D. C., Czech. J. Phys. **50**, 893 (2000)

[4] Birkett A. J., Corner W. D., Tanner B. K., Thompson S. M., J. Phys. D: Appl. Phys. **22**, 1240 (1989)

[5] Hwang D. G., Kim H. C., J. Phys. D: Appl. Phys. **21**, 1807 (1988)

[6] Vicena F., Czech. J. Phys. **5**, 480 (1955)

[7] Trauble H., Moderne Probleme der Metall Physik, Vol. 2, Berlin: Springer (1966)