Bulgarian Society for NDT
International Journal "NDT Days"
Volume III, Issue 5, Year 2020
ISSN: 2603-4018
eISSN: 2603-4646

Investigation of Influence on Mechanical Stress to Change in Magneto Noise and Magneto Electro-acoustic Characteristics in Ferromagnetic Steel

Yordan N. MIRCHEV[1], Pavel N. IVANOV[2], Desislava L. PASHKULEVA[1], Mitko M. MIHOVSKI[1], Boris G. VELEV[1], Valeriy L. VENGRINOVICH[3]

[1] Institute of Mechanics at the Bulgarian Academy of Sciences, Sofia, Bulgaria,
e-mails: mirchev@imbm.bas.bg, nntdd@abv.bg.

[2] National University of Science and Technology "MISiS", Moscow, Russia,
e-mail: pavelnivanov@mail.ru

[3] Institute of Applied Physics of the National Academy of Sciences of Belarus, Minsk, Belarus,
e-mail: veng@iaph-bas.net.by

Abstract
The paper presents the results of complex research on low carbon steel S235. The research was carried out using electromagnetic methods, the Barkhausen noise method and a magnetic-acoustic emission method with the Multitest-MS10 equipment developed at the Institute of Mechanics (IMech) – Bulgarian Academy of Sciences (BAS).

Keywords: Barkhausen noise, magnetic-acoustic emission method, mechanical stress strain.

1. Introduction

To assess the mechanical stresses (operating and residual) in ferromagnetic steels, non-destructive testing methods are successfully used – ultrasonic (using bulk, surface, subsurface waves), eddy current, electromagnetic and others. The present work focuses on the use of electromagnetic methods. The basis of these measurements are the correlations between mechanical stresses, on the one hand, and the main magnetic characteristics of ferromagnetic materials (hysteresis dependences, differential magnetic permeability, coercive force, residual magnetic induction, magnetic permeability, the ratio of magnetic induction to coercive force) and others [1 ÷ 3, 8].

In recent years, a number of studies have appeared in the literature and suitable devices have been developed based on the relationship between the magnetic noise voltage of Barkhausen and the magneto-acoustic emission response of ferromagnetic materials from mechanical stresses [4, 5, 7].

The present work is dedicated to the complex use of these parameters and the developed device Multitest – MS 10 in IMech – BAS for evaluation of mechanical stress state in steel S235 [9].

2. Formation of magnetic structures under the action of mechanical deformations

Theoretical and experimental dependences allow realizing successfully practical tasks for determination of the acting mechanical stresses in ferromagnetic materials. The physical basis is the formation of magnetic structures under the action of mechanical stresses.

The basis of magnetoelastic effects is the phenomenon of magnetostriction. It occurs in the material when its temperature is lower than the Curie temperature for the material under the action of bulk energy, interatomic forces in the lattice, the energy of crystallographic anisotropy, the energy of magnetostrictive deformation and magnetoelastic energy.

The dependence of magnetostriction $\lambda = \Delta l/l$ (relative resizing) depends on the magnetic field. At small values of the field strength λ increases, reaches maximum values and then decreases and changes its sign. For ARMCO iron, the values of λ are in the range from 0 to 5.10^{-6} and then to -5.10^{-6} [1].
Figure 1 shows the experimental dependences of λ on the mechanical tensile load for steel 45 on the intensity of the magnetic field H [2].

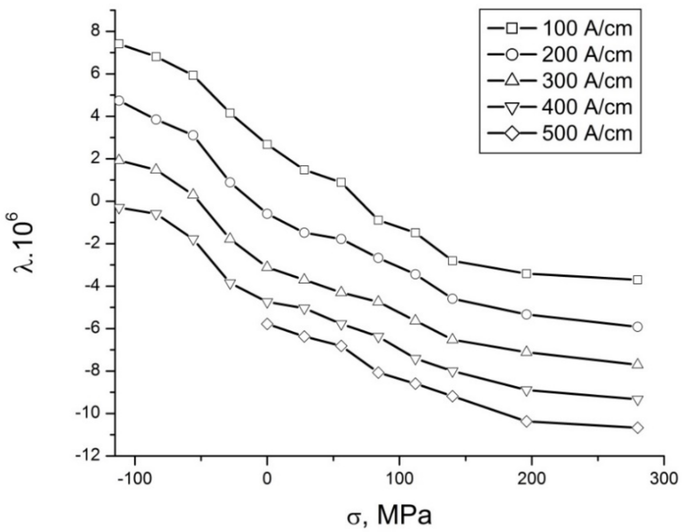


Fig. 1 Dependence of λ and σ at different values of magnetic field strengths for steel 45.

In most alloyed ferromagnetic steels the magnetostriction λ with increasing magnetic field strength H is positive, as maximum values are reached at a voltage of 150 – 200 A / cm. With increasing intensity of magnetic field H, λ decreases. From the dependences of Fig. 1 it follows that at higher values of H the dependence $\lambda = F(\sigma)$ unambiguously decreases.
The ferromagnetic material can be considered as a structure consisting of magnetic domains with 180° and 90° orientation of the walls. When the material is magnetized in the process of changing the magnetic field strength in the magnetic structure, the state of all domains changes. But only when the magnetization allows the inclusion in the magnetization process of 90° domains occurs the appearance of magnetostrictive deformation. Conditions are created for generating acoustic waves. The magnetostrictive deformation of 180° domains is negligible. The field strength, respectively the magnetizing current in the coil, is called the critical field H_c or the current I_K of occurrence of magneto-acoustic emission activity. When the tensile load is formed, a new magnetic structure is formed as the domains are oriented in the direction of the applied load.

3. Measurable magnetic characteristics

The following measurable characteristics are used in the work – average value of Barkhausen magneto-noise voltage U (NB), voltage proportional to the integrated value of magneto-acoustic emission U (MAE) and critical value of magnetizing current I_K at which the appearance of acoustic emission begins. The magnetic field strength H is uniquely determined by the magnetizing current I_H and the parameters of the used magnetizing coil.
Based on the research in [3 ÷ 7] the following dependences between the measurement characteristics, the magnetic properties of the materials and the experimental conditions can be presented.

3.1. Magneto-noise voltage

In ferromagnetic material, the domain structure at zero magnetic moment (in the absence of external magnetic fields) is energetically powerful and corresponds to the minimum free energy. When a magnetic field is applied in the material, an abrupt re-magnetization of the domains or the cluster of them is observed. In steels, the duration of the induced signals in the measuring coil has of the order of $10^{-7} \div 10^{-8}$ s and depends on the thermal, structural and deformation state of the material. The volume of the pre-magnetized region is of the order of $10^{-7} \div 10^{-8}$ mm^3.

The total induced electromotive force in the coil of the transducer from random and independent Barkhausen jumps occurring in the magnetizing volume of the object under the influence of an alternating magnetic field, taking into account the transverse state of materials is represented by the equation.

$$U = k.\int_0^{\infty} \frac{\mu_0.\Delta J_S .\bar{v}.s}{2 .r^{-3}} .exp\left[-\frac{t}{r_\delta}.\sigma(r)\right].exp(-r/r_u)dr, \tag{1}$$

where k=dn/dr is the density of the jumps in a uniform magnetic field in a volume of thickness dr (a quantity that can be assumed in the first approximation of a constant), $\Delta\bar{\Phi} = \mu_0.\Delta J_s .\bar{v}.s/2 .r^{-3}$- change of the induction flow in the receiving coil with area s when the average magnetic moment changes $\mu_0.J_s .\bar{v}$ at a distance r from the axis of the coil, $\bar{v}$ – average volume of the pre-magnetized area, ΔJ_s – change in magnetic saturation, $\sigma(r)$ – a function that takes into account the influence of mechanical stresses in the material, r_u – distance of the coil to a layer in the material from which the signal decreases exponential.

3.2. Magneto-acoustical emission

Assuming that the MAE measurement is performed at a given distance from the domain that creates the acoustic wave in [6, 7] the following dependence is proposed to describe the degree of deformation caused by a spontaneously deformed spherical domain with radius R_g

$$\vec{U}^c(r,t) = \vec{U}^c(r) + \frac{R_g^3}{3.\pi.r^2}.\vec{F}(r,t) , \tag{2}$$

where

$$\vec{F}(r,t) = \frac{\overrightarrow{\sigma_r^0}}{\mu} - \left[cos\left(\omega_0.\frac{r}{c_t}\right) - cos\left(\omega_0.\frac{r}{c_t}\right)\right] + \frac{\overrightarrow{e_r}}{\lambda + 2.\mu}.\left[cos\left(\omega_0.\frac{r}{c_t}\right) - cos\left(\omega_1.\frac{r}{c_t}\right)\right] - \frac{\overrightarrow{e_r}}{\mu}.\left[cos\left(\omega_0.\frac{r}{c_l}\right) - cos\left(\omega_1.\frac{r}{c_l}\right)\right],$$

where r is the distance from the domain on the transducer for registration of MAE, t – time, R_g – domain radius, ω_0- resonant oscillation frequency of the domain, c_t and c_l – transverse and longitudinal velocity of propagation of the elastic wave, μ – magnetic permeability, σ_r – internal mechanical stresses in the volume.

The dimensions of the areas of spontaneous re-magnetization and emission of acoustic signals are $10^{-2} \div 10^{-6}$ mm^3 and are significantly smaller than the length of the ultrasonic wave in the material. The domain as it deforms is a point source and the created acoustic field has a longitudinal and transverse component.

3.3. Critical field for excitation of magnetic acoustic emission signals

A model for modeling a single signal of MAE is proposed. Each domain is surrounded by other domains, due to which it cannot acquire its spontaneous deformation during re-magnetization. It oscillates as generate signals in a certain frequency range, which are registered with an acoustic emission transducer. For a spherical shape of the domain, the critical value H of the voltage H_c (which is achieved at certain critical values of the magnetizing current I_K in a magnetizing coil) is represented by the dependence [6, 8].

$$H_c \approx \frac{\lambda_s.\sigma}{\mu_0.M_s} + \frac{\gamma}{\mu_0.M_s.D_Д} = H_k + \frac{\gamma}{\mu_0.M_s.D_Д}\,, \tag{3}$$

where M_s e magnetization per domain, λ_s – the magnetostriction of the domain material at saturation, σ – represents the cumulative action of internal mechanical stresses, γ – change in the limit energy density, μ_0 – magnetic permeability of the air, H_k – maximum value of the critical field, $D_Д$ – domain diameter.
It can be seen that the critical field H_K depends on the magnetic characteristics of the material, the internal mechanical stresses σ, the magnetostriction of the material at saturation, change of the limit energy γ, the size of the domain.

4. Test object

The material from which the test specimens are made is low carbon steel grade S235, according to EN 10025. Disproportionate test specimens with dimensions 3,2 × 30 mm^2 and initial measuring length 140 mm, according to EN ISO 6892- 1: 2009. The test specimens have suitable dimensions for the non-destructive testing. The test specimens are defect-free and of high roughness quality. The roughness is Ra ≈ 6.3 μm.

5. Equipment. Methods.

An upgraded universal test machine, model ZD 10 / 90 with a working range of up to 100 kN, was used to create tensile stresses in the test specimens. The equipment has a control section with software for data collection, processing and analysis.The researches for determination of the magnetic-noise and magneto-acoustic emission voltages generated in the samples were carried out using a developed device MULTITEST MS 010 [9], intended for complex magneto-noise and magnetic-acoustic emission control of ferromagnetic materials. Appearance of the equipment is presented in Fig.2.
Noise voltage U (NB) is measured in the frequency range from 10 KHz to 100 KHz, limited by appropriately tuned filters. The U (MAE) is recorded using a Valen wideband acoustic emission transducer with a frequency band from 100 KHz to 450 KHz. The magnetizing current I_H varies from 0 to 450 mA.

Fig. 2. Equipment for complex non-destructive testing MULTITEST MS 010

6. Experimental Testing.

The first stage of the study includes a classical uniaxial tensile test to fracture of the specimen, according to the requirements of standard EN ISO 6892. The test was performed at room temperature (23±2) ºC, and a deformation rate of 0.1 mm / s. The stress-strain diagram was constructed and the basic load curve of the specimens without testing with the Multitest-MS 010 device was obtained. The elastic zone and the tensile strength were determined for the tested material.

Non-destructive testing using the Multitest-MS 010 device was performed on the prepared samples. The transducer for generating and receiving magnetic-noise voltage is attached to the sample without contact medium, and the magnetic-acoustic transducer is attached as there is a layer of grease between the sample and the transducer.

The information characteristics of the tests performed are: the average value of magnetic-noise voltage U (NB), magneto-acoustic emission U (MAE) and critical current in the magnetizing coil I_K at which the recording of acoustic emission signals begins.

Variable parameters in the tests performed are: mechanical stress stain σ in MPa caused by uniaxial tensile load and magnetizing current I_H for excitation of Barkhausen noise and magneto-acoustic emission.

In magnetic tests, the test specimen is loaded with a gradually increasing force and a measurement is made after holding. The measurement is acquisition with step of loading 2.5 kN. The measurements are performed only in the zone of elastic deformations befor the yield strength is reached until loading of 17 kN.

7. Experimental results.

The main dependence of the mechanical stress – deformation for the samples is shown in Fig.3. On it are determined, respectively, yield strength Re = 250 MPa and tensile strength Rm = 400 MPa.

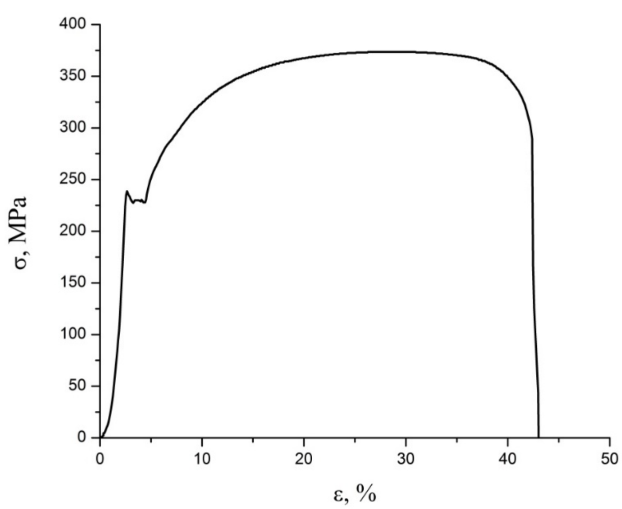
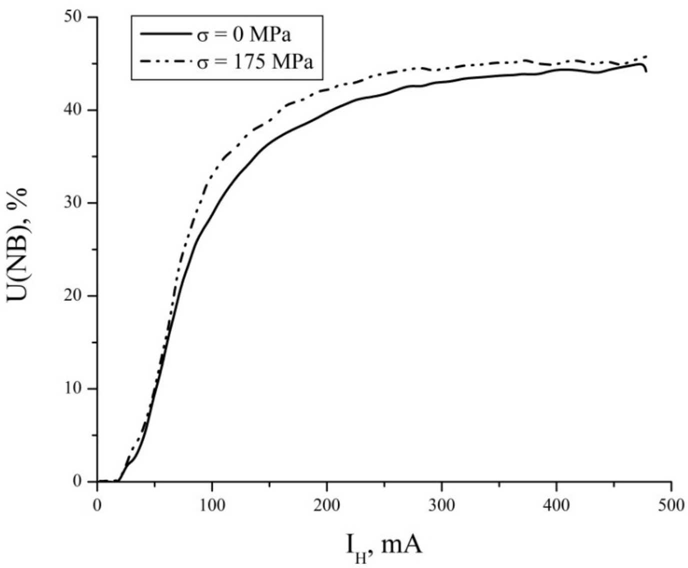


Fig. 3. Tensile diagram for sample steel grade S235

Numerous measurements of the magnetic noises U (NB) and magnetico-acoustical emission have been performed, when the mechanical stresses change, at different values of current and frequencie band for magnetization. The dependences of U (NB), U (MAE) and I_K measured with the Multitest – MS 10 device are presented in Fig. 4, Fig. 5 and Fig. 6, respectively.



Фиг.4. Dependence of U (NB) in the tested samples on the magnetizing current I_H in the sample without load σ = 0 MPa and with load σ = 175 MPa.

The magnetizing current I_H at which the change in voltage U (NB) reaches saturation is 400 mA.

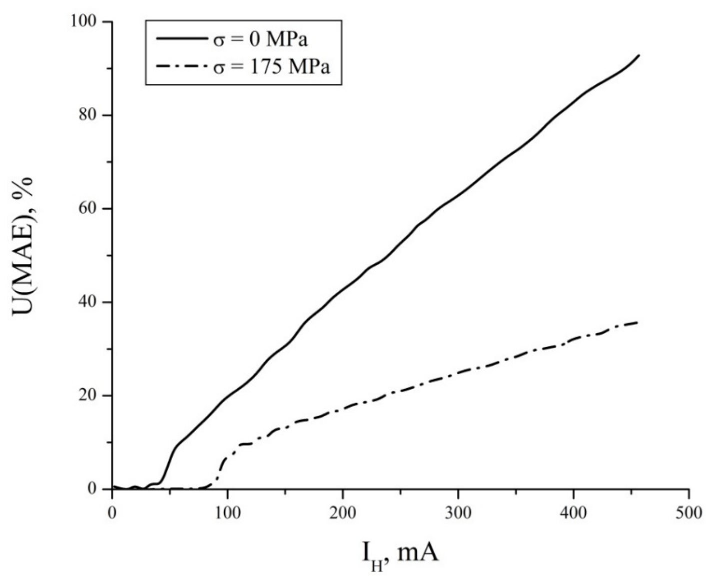


Fig.5. Dependence of the voltage of magneto-acoustic emission U (MAE) in the tested samples on the change of the magnetizing current I_H, without load σ = 0 MPa and with load σ = 175 MPa.

If U (MAE) = 2% is assumed, it is observed that the beginning of the magnetic-acoustic activity begins to increase for an unloaded sample at I_H = 43 mA, and for a loaded sample with σ = 175 MPa at I_H = 90 mA. The magnetic-acoustic emission activity in the mechanically loaded samples is lower.

The critical magnetizing current I_K, at which the registration of MAE begins with an unloaded sample, is 43 mA, and the voltage U (MAE) is 2%.

Dependence for U (MAE) at I_H = 450 mA on the mechanical stresses σ is presented in Fig.7.

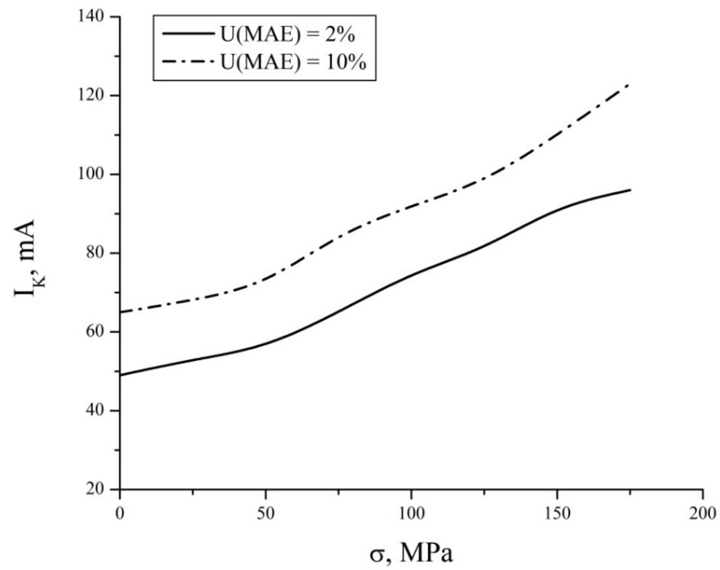


Fig.6. Dependence of the critical magnetizing current I_K at which the registration of U (MAE) starts at the level of 2% and 10% of the mechanical stresses σ in the sample

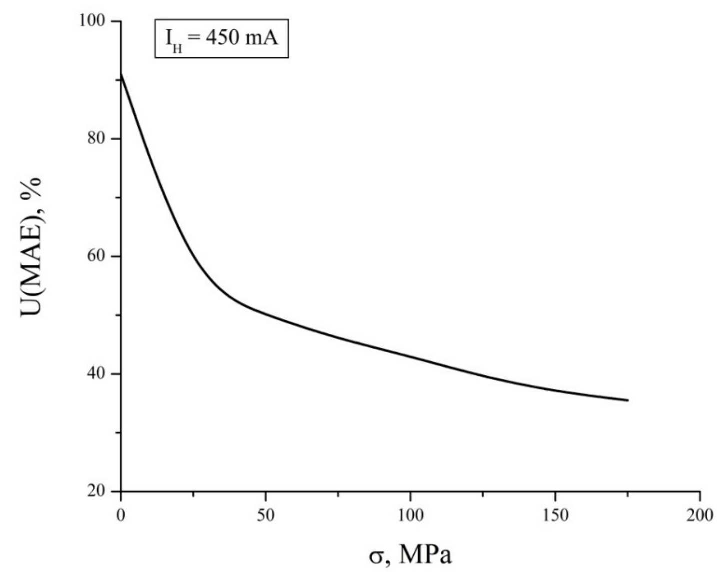


Fig.7. Dependence of the voltage U (MAE) of the magnetoacoustic emission, at magnetizing current I_H = 450 mA on the tensile stresses σ in the tested sample.

8. Conclusion

The measurements performed with the Multitest-MS 010 device show that it is applicable for evaluation of mechanical stresses in ferromagnetic materials.
The dependence of the average value of the magnetic noise voltage U (NB) on the magnetizing current is particularly pronounced for a magnetizing current up to 200 mA.
The dependence of U (MAE) on the magnetizing current I_H is close to linear, being particularly strongly influenced by the sample load. As the tensile stresses increase, U (MAE) decreases.

When the sample is loaded, the beginning of the acoustic signal curve (registration of magnetic-acoustical emission) is registered at increased values of the magnetizing current I_H relative to the unloaded sample.

The dependence U (MAE) on the mechanical stresses σ is practically linear at loads above 25 MPa.

It is recommended to use all three parameters – U (NB), U (MAE) and I_H in the technical instruction for inspection of the mechanical stress state.

Acknowledgements

This research was funded by

- NUST MISIS Competitiveness Program, grant No. "K2-2019-004"
- Project "Studying the effect of mechanical stresses on ferromagnetic materials using acoustic methods, Barkhausen effect and others to develop non-destructive methods to determine the technical state of gas pipelines, oil pipelines and heat transmission systems at nuclear power plants" between the Institute of Mechanics at the Bulgarian Academy of Sciences and the Institute of Applied Physics at the National Academy of Sciences of Belarus.

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