Bulgarian Society for NDT
International Journal "NDT Days"
Volume I, Issue 1, Year 2018 ISSN: 2603-4018

On the Correlation of the Residual Magnetic Induction of Matter and the MAE Parameters in Ferromagnetic Materials

Vladimir N. KOSTIN[1,2], Evgeniy D. SERBIN[1,2]

[1] M.N. Mikheev Institute of Metal Physics of Ural Branch of Russian Academy of Sciences; Yekaterinburg, Russia; Phone: +7 343 378 3659; e-mail: kostin@imp.uran.ru, sseugene30@gmail.com
[2] Ural Federal University n.a. B.N. Yeltsin; Yekaterinburg, Russia

Abstract
The complex of magnetic and magnetoacoustic properties of cold-deformed and annealed, as well as quenched and tempered steels of various chemical composition is studied. It is established that the amplitude-frequency parameters of magnetoacoustic emission (MAE) of the investigated steels correlate with the residual magnetic induction of steel's matter. It is shown that application of the MAE technique provides a sufficiently universal set of parameters suitable for the testing of softening thermal treatments along with a residual magnetic induction of ferromagnetic steels. The amplitude of magnetoacoustic emission can be used as a testing parameter in scanning systems of structuroscopy of ferromagnetic materials. The possibility of contactless excitation and detection of magnetoacoustic emission by means of electromagnetic-acoustic transformation (EMAT) can allow carrying out the rapid evaluation of ferromagnetic objects structural-phase state.

Keywords: magnetic properties, residual magnetic induction, magnetoacoustic emission, magnetoacoustic parameters, structural sensitivity, magnetic properties of matter, ferromagnetic materials

1. Introduction

Recently, diagnostics of extended loaded steel objects (pipelines, suspensions, rails, etc.) has become more and more urgent. In cases of diagnostics of massive long objects scanning of the monitored surfaces is required, which, in turn, requires the measurement of the necessary testing parameter (or several parameters) to be repeated with the desired frequency of measurement [1]. In addition, the measurement of some magnetic parameters (e.g. permeability) requires thorough demagnetization of the tested objects, and therefore it is extremely difficult to use these parameters in practical applications for monitoring of the structural state of ferromagnetic objects. It is usually necessary to know the magnetic properties of ferromagnets as a function of a true, internal magnetic field. However, in most practical cases, the dependence of the magnetization on the external magnetic field is measured. Many proposed methods of magnetic testing are very complex, time-consuming and more suitable for laboratory research [1,5]. The measurement of the magnetic parameters that are related to the cyclic magnetization reversal along symmetric or asymmetric hysteresis loops is a lot simpler to conduct. Also, the problem of the residual magnetization of tested object naturally eliminates with the use of an alternating magnetic field.

Multiparameter diagnostics, based on the measurement of a complex of structurally sensitive magnetic characteristics, as well as parameters characterizing the dynamics of domain structure rearrangement during magnetization reversal, can provide a more reliable determination of the structural-phase and stress-deformed states of tested ferromagnetic object. The magnetoacoustic emission (MAE) is understood as the whole set of elastic vibrations arising in a ferromagnet upon its cyclic remagnetization. In case of low-frequency magnetization reversal of ferromagnets, the main mechanism of MAE is magnetostriction, which manifests itself in a change of the sample size, as well as in the appearance of local elastic perturbations, mainly caused by irreversible displacements of 90-degree domain walls (magnetic noise). Accordingly, magnetoacoustic emission bears information on the local magnetostrictive interactions of the entire remagnetized volume of the object associated with irreversible displacements of the 90-degree domain walls and makes it possible to register jumps of domain boundaries not only near the surface, but also in the volume of the material [1-4]. Studies of the relationship between magnetoacoustic emission and the magnetic parameters of structural-phase state of various materials, including those subjected to thermal and deformation effects, have a fairly long history and have not lost their relevance to the present time.

Thus, the aim of this study was to show the correlation between magnetoacoustic testing parameters and residual magnetic induction of ferromagnetic steels after different heat-treatments and to identify the magnetic and magnetoacoustic parameters suitable for the use in nondestructive testing techniques and diagnostics of ferromagnetic materials.

2. Materials and Experimental Methods

The first group of samples from steels 20G and 70G were subjected to cold plastic deformation by rolling to respectively 40% and 63% (by variation of the cross-section) to vary stress-strain state within a wide range and then samples were annealed at different temperatures in the range from 20 to 800°C for 1 hour followed by cooling in air. The samples were then ground to remove the scale and the decarburized layer. The final dimensions of the 20G steel samples were 4x10.2x69 mm, and the 70G steel was 6x9.5x88 mm.

The second group included heat-treated samples from structural steels 09G2, 35. The choice of these steels was, on the one hand, due to the need to assess the effect of carbon content on the dependence of the magnetoacoustic parameters studied on the heat treatment regimes, and on the other hand, to the lack of effective methods for controlling of the medium- and high-temperature tempering of these steels. Samples of steels 35 were heated to 850°C and after soaking for 10 minutes were quenched in water at room temperature. Steel 09G2 was similarly hardened from 930°C into water. Further, the hardened steel samples were tempered at various temperatures in the range of 20-700°C.

The samples of the first group were brought to the final dimensions of 3.8x6.1x86.2 mm and the second group samples to 10x10x62 mm by grinding with a small circular feed and intensive cooling. The coercive force of all the samples studied after the grinding has changed insignificantly, which indicates the absence of appreciable plastic deformation during grinding.

3. Results and Discussion

In order to determine the practical possibility of applying residual magnetic induction as a parameter for controlling the stress-strain state measurements of its value were made using the hardware-software system DIUS-1.15M [6]. The results of the measurements are shown in Fig. 1. The values locally measured with the help of an attachable U-shaped electromagnet correlate well with the magnitude of the residual magnetic induction of the substance. It must, however, be noted that the measurement of the residual magnetic induction of a substance is possible only with good contact of the surface of the tested object and the poles of the electromagnet. Presence of the gap in the "transducer-object" circuit changes the structural sensitivity of the measured characteristic (the structural sensitivity of the residual magnetic induction of the body is close to the structural sensitivity of the coercive force). Thus, the development of contactless methods of measuring of the residual magnetic induction value is an actual and practically significant task [1]. Another way of dealing with this problem is to search alternative structure-phase sensitive parameters based on the dynamics of domain structure rearrangement during magnetization reversal, such as amplitude-frequency characteristics of magnetoacoustic emission [4].

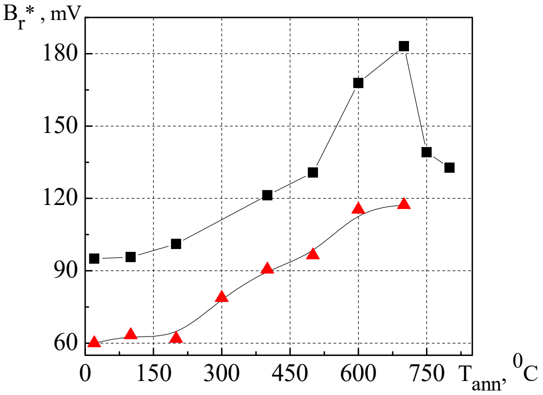

Figure 1. The dependences of the relative values of the residual magnetic induction of the substance on the annealing temperature of the specimens from the 20G (red triangles) and 70G (black squares) steels, measured with the use of hardware-software system DIUS-1.15M

Fig. 2 shows the dependences of the amplitude of the MAE (U_{MAE}) and the residual magnetic induction B_r on the annealing temperature of samples from cold-deformed and annealed 20G and 70G steels. In Fig. 2 is clearly seen correlation between the residual magnetic induction and the amplitude of the MAE. Attention should be drawn to the similarity of the dependencies $U_{MAE}(T_{ann})$ and $B_r(T_{ann})$. When the annealing temperature is increased in the range (20-700) ^{0}C, the values of the U_{MAE} of steels 20G and 70G increase approximately by 2 times, which is comparable with the change in the residual magnetic induction of these materials. With the possibility of contactless excitation and detection of magnetoacoustic emission by electromagnetic-acoustic transformation (EMAT) the amplitude of MAE can be an alternative parameter to the residual magnetic induction which will eliminate the need to carry out complex procedures of conventional electromagnetic testing techniques.

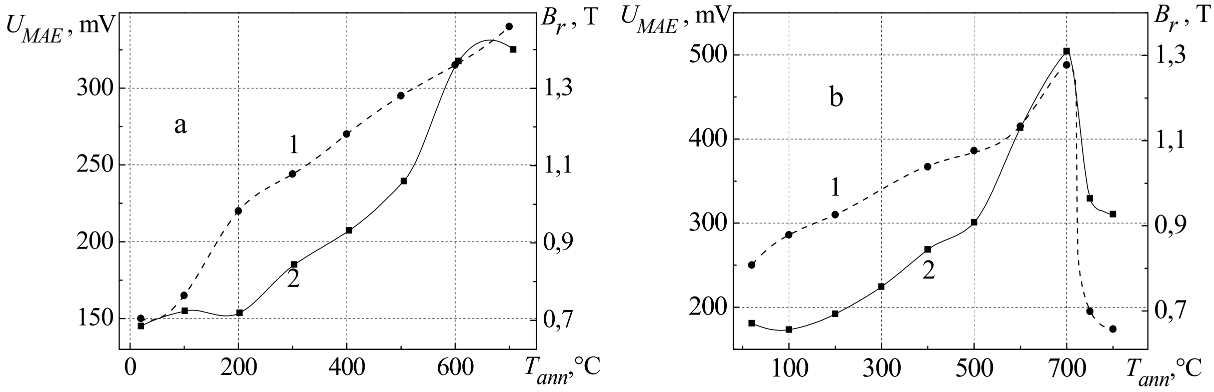

Figure 2. Dependences of MAE amplitude (1) and residual magnetic induction (2) on the temperature of annealing of samples of cold-deformed and annealed steels 20G (a) and 70G (b)

The processes of restructuring of the domain structure have different dimensional (e.g. the area of jump or the mean free path of the domain wall), quantitative (e.g. the number of simultaneously shifting boundaries) and temporal (e.g. Barkhausen jump time) parameters. The resulting MAE signal is also affected by the reflection of elastic oscillations from the boundaries of the ferromagnet and, as a consequence, the MAE parameters depend on the shape and size of the magnetized object. All these features are reflected in the MAE frequency spectrum [4].

The dependence of the fundamental frequency of MAE signal averaged over five measurements on the annealing temperature of 70G steel is shown in Fig. 3. The value changes by no more than 12%, which makes its application problematic for the testing of the annealed 70G steel.

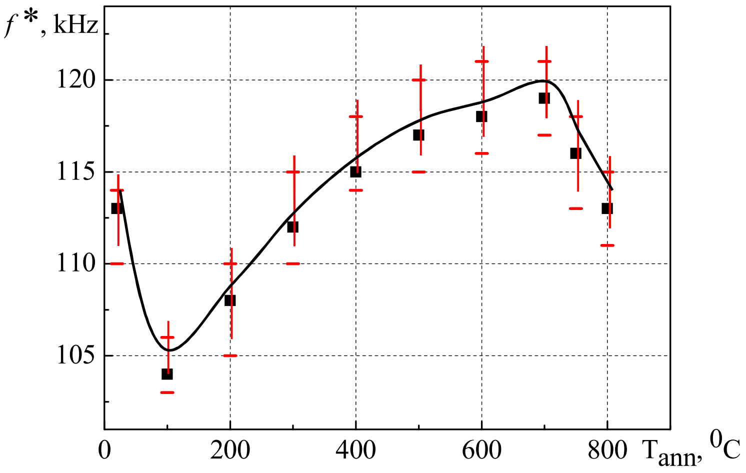

Figure 3. Dependence of the main frequency of the MAE signal on the annealing temperature of 70G steel (magnetization reversal frequency = 4 Hz)

Fig. 4 shows the dependences of the amplitude A_{av} and the fundamental frequency f^* of the magnetoacoustic emission signal, averaged over all frequencies, determined at different frequencies of magnetization reversal, on the temperature of tempering the 09G2, 35, and steels.

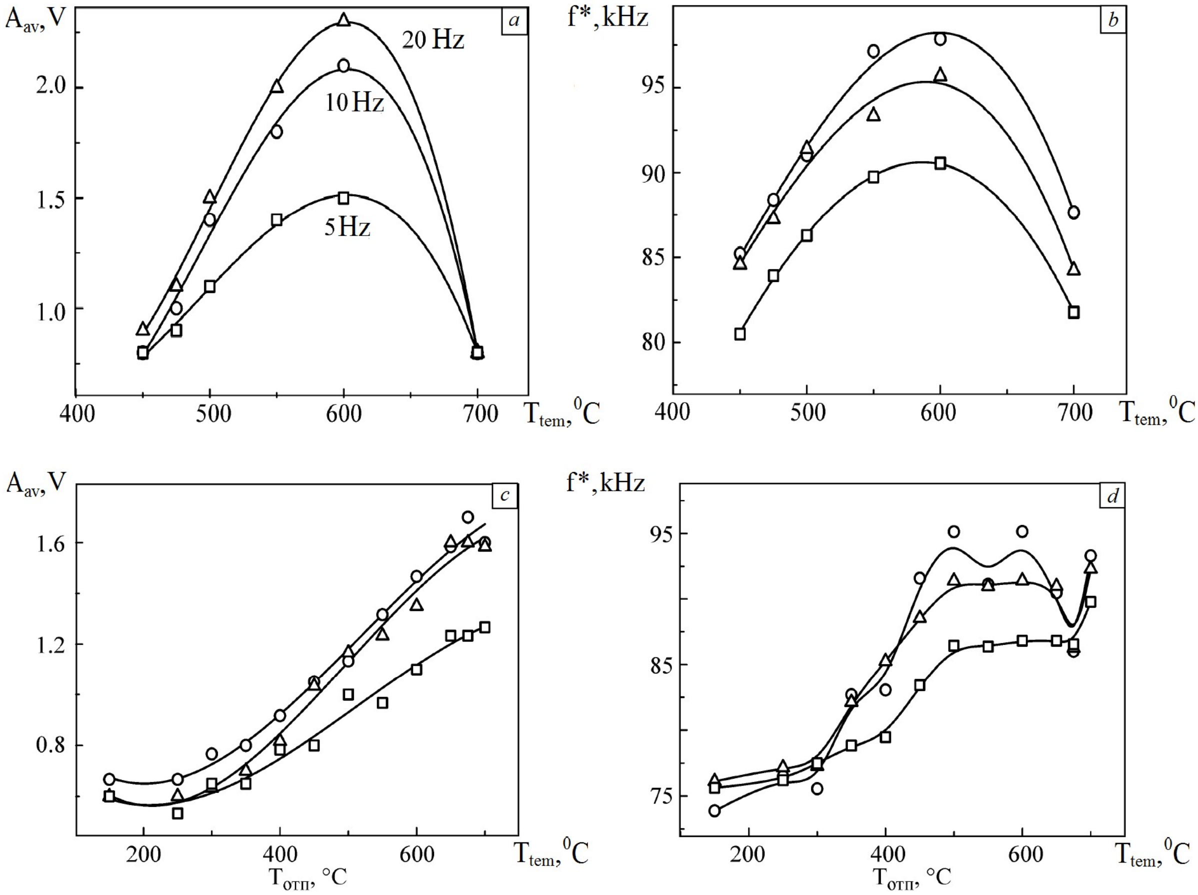

Figure 4. Dependences of the averaged amplitude (a, c) and the fundamental frequency (b, d) of the magnetoacoustic emission signal from the T_{tem} of steel 09G2 (a, b) and steel 35 (c, d) determined at different frequencies of magnetization reversal

For low-temperature tempered samples of 09G2 steel a high level of acoustic noise hinders the spectral analysis of the signal of magnetoacoustic emission. However, as can be seen from Fig. 4a, an increase in the tempering temperature from 450 to 600°C leads to a monotonic increase in the A_{av} value, and this value increases more than two-fold. With a further increase in temperature to 700°C, the amplitude A_{av} decreases to values comparable with noise. The fundamental frequency of magnetoacoustic emission f^* also has a maximum at T = 600°C (Fig. 4b). It should be noted that the nature of the change in the values of A_{av} and f^* during the variation of tempering temperature is independent of the frequency of the magnetization.

As can be seen from Fig. 4 (c, d) the dependences $A_{av}(T_{tem})$ and $f^*(T_{tem})$ have different character for steel 35. At all the indicated remagnetizing frequencies, the amplitude A_{av} increases monotonically with increasing T_{tem} in the range 250-700°C. The fundamental frequency rises to T_{tem} = 500°C, and at a higher temperature f^* varies weakly and unequivocally. For this steel, the most convenient parameter of tempering testing is the amplitude A_{av}.

A certain difference in the behavior of the parameters A_{av} and f^* may be due to the fact that the frequency f^* should be determined by the number of 90-degree domain walls in the material, and the amplitude A_{av} is the volume of remagnetizable regions with 90-degree neighborhoods.

The dependences of $B_r(T_{tem})$ of two of the investigated steels are presented in Fig. 5. It can be seen that the value of B_r of steel 09G2 increases to T_{tem} ~ 550-600°C and sharply decreases with a further increase in the temperature of tempering. The residual magnetic induction of steel 35 reaches its maximum value at T_{tem} = 500°C and weakly changes with a further increase in tempering temperature.

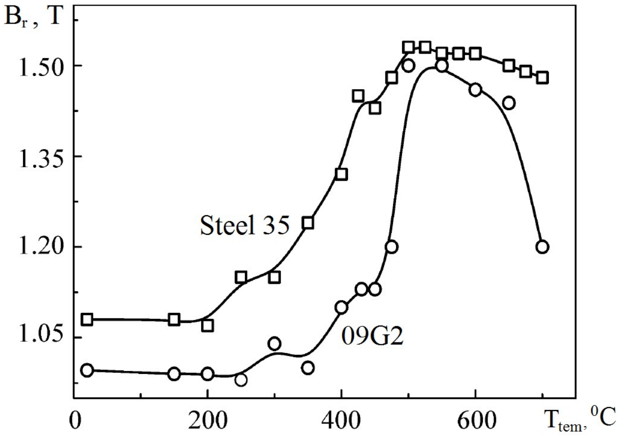

Figure 5. Dependence of the residual magnetic induction on the tempering temperature of steels 35 and 09G2

Comparison of Fig. 5 with Fig. 4 (a-d) shows that the parameters A_{av} and f^* behave similarly to the residual induction B_r. This similarity can be explained by the fact that the residual magnetic induction depends to a large extent on the 90-degree domain boundaries subsystem, which at the same time is the source of magnetoacoustic emission. The increase in B_r with increasing temperature of the tempering of quenched steels is due to the improvement in the crystallographic structure of materials, such as removal of internal stresses, grain growth, and coagulation of carbide particles.

4. Conclusion

The existence of a relationship between the residual magnetic induction of matter and the amplitude of magnetoacoustic emission of annealed steels 20G and 70G is established, which consists in correlation of the dependences of these parameters on the annealing temperature of steels. For the evaluation of annealing MAE amplitude can be used as an alternative parameter of testing along with the residual magnetic induction.

The fundamental frequency of MAE signal of annealed steels changes nonmonotonically and does not show correlation with the residual magnetic induction. On the contrary, MAE signal amplitude and fundamental frequency of tempered steels shows correlation with the residual magnetic induction, which allows to recommend amplitude and fundamental frequency of MAE as an alternative parameters for the testing of heat-treatment quality testing of ferromagnetic steels after softening treatments.

The possibility of contactless excitation and detection of magnetoacoustic emission by means of electromagnetic-acoustic transformation (EMAT) can allow carrying out the rapid evaluation of ferromagnetic objects structural-phase state.

The reported study was funded by RFBR according to the research project № 18-38-00253.

References

1. Kostin V.N., O.N. Vasilenko, D.Yu. Filatenkov, Yu.A. Chekasina, E.D. Serbin, 'Magnetic and magnetoacoustic testing parameters of the stressed–strained state of carbon steels that were subjected to a cold plastic deformation and annealing', Russian Journal of Nondestructive Testing, Vol 51, No 10, 2015, pp 624-632.
2. Kostin V.N., D.Yu. Filatenkov, Yu.A. Chekasina, O.N. Vasilenko, E.D. Serbin, 'Features of excitation and detection of magnetoacoustic emission in ferromagnetic objects', Acoustical Physics, No 2, 2017, pp 237-246.
3. Kostin V.N., E.D. Serbin, O.N. Vasilenko, 'The interrelationships of magnetic and magneto acoustic-emission characteristics of heat-treated steels of various chemical composition', MATEC Web of Conferences, Vol 145, Article No 05005, 2018, pp 1-7.
4. Kostin V.N., M.A. Guriev, O.N. Vasilenko, D.Yu. Filatenkov, Y.G. Smorodinsky, 'Amplitude-frequency characteristics of magnetoacoustic emission of heat-treated Fe-based alloys', Physical Mesomechanics, No 16, 2013, pp 103-110.
5. Kostin V.N., V.I. Pudov, E.D. Serbin, O.N. Vasilenko, 'Magnetoacoustic hardness testing of cold-deformed and heat-treated carbon steels', Deformation and Fracturing of Materials, No 2, 2017, pp 41-46.
6. Kostin V.N., A.V. Kadrov, A.E. Kuskov, 'Magnetic Properties of a Material Used to Estimate Elastic and Plastic Strains of Ferrite-Pearlite Steels', Russian Journal of Nondestructive Testing, Vol 41, No 10, 2005, pp 632-639.