Scanning steel junctions using eddy current probe

A Ishkov¹, V Malikov², S Dmitriev², D Fadeev², A Katasonov², K Rykova²

¹ Department of technology of construction materials and repair of machines, Altay State Agricultural University, Barnaul, Russia
² Physical-technical faculties, Altai State University, Barnaul, Russia

E-mail: mirotnas@gmail.com

Abstract. The aim of this research is the process of developing a miniature probe for studying electrical steel. The issue of safety when using the products made of this type of steel, assessment and forecast of their quality make this topic relevant. We have found it possible to study the characteristics of steel at different depths by changing the signal amplitude generated by the eddy current probe. The novelty of this research is due to the use of a superminiature eddy current probe of a transformer type that can perform point measurements (0.05 mm sections) of ferromagnetic materials using the eddy current method and is based on the study of conductivity of electrical steel. A hardware and software package is designed based on the developed probe. It can test steel at its boundary with a dielectric. A system that can automatically move the probe over a controlled object at a preset speed has been developed. The study consisted of continuous and discrete measurements that were made by moving the probe over a ferromagnetic and dielectric material at a given speed and scanning the object in 0.1 mm increments. The results of the test performed on samples at different measurements and at different frequencies from 2000 to 20000 Hz are indicated. The study showed that the magnetic field lines of steel, which occur as a result of the impact of the eddy current probe on the ferromagnetic material, have a strong effect on the signal received by the eddy current probe after it is removed from the controlled object at a distance of 1 mm. The signal frequency on the exciting coil of the eddy current probe has a significant influence on this process. The conducted tests have demonstrated the nonlinear nature of the dependency of the probe response when it passes through the steel-dielectric boundary; the mathematical regularity of this dependency is revealed. The effect of the gap between the eddy current probe and the object of study is also analyzed.

1. Introduction
Currently, the task of evaluating the quality and reliability of production facilities is relevant. The control methods used give reliability estimates based on probabilistic approaches, and the determination of reliability parameters is based only on actual data, such as operating mode, material stress, deformation and temperature. Unfortunately, these methods hardly consider the changes that occur in the metal. It is known that under the influence of load, the metal changes, and changes occur both in the volume and on the surface of the material. Thus, we can conclude that it is necessary to develop new devices and methods that allow us to study structural changes occurring in the metal and register the properties of its surface.

Electrical steel is one of the metals, which can be studied. The use of electrical steel is quite widespread. It is used in manufacturing products used in electrical engineering. Steel has various
magnetic properties that are used in the development of modern methods of control, as well as for the
diagnostics of its characteristics, including physical and mechanical ones. These characteristics
determine the reliability of products, the predicted service life, the service life of their main parts and
components used in various industrial spheres. Control of the main properties of ferromagnetic steel by
hysteresis parameters, as well as magnetic and magneto-acoustic noise, is demonstrated in studies [1].

One of the most effective methods to study mechanical characteristics of steel is an eddy current
method [2]. This method is widely used in non-destructive testing. It is based on the analysis of the
electromagnetic field change caused by eddy currents of the material under study, which are induced by
the primary electromagnetic field.

In 1986, at the international academic conference of the review of progress in quantitative NDE, Auld
and Marinov et al presented the concept of eddy current array sensors [3]. It marked the birth of
the eddy current array testing (ECAT), which can directly detected without cleaning the surface of the
workpiece, and effective testing the surface and near surface defects of the austenitic stainless steel. The
C scan map can make the defects intuitionized, the phase of the impedance map can determine the true
or false of the defect, and the strip map can make a preliminary quantitative analysis of the defects.
Taniguchia [4] carried out research on ECAT image, used image processing algorithm to determine the
specific location of defects. He [5] simulated the mutual inductance between the coil units of the eddy
current array sensor using the three-dimensional finite element method. Liu [6] established a mapping
relationship between the crack length, depth and the time domain characteristics of the detected output
signal in the light of the transmitting and receiving eddy current array sensor. Machand [7] designed a
flexible eddy current array probe which used to detect the complex surfaces samples, the probe was very
sensitive to micro defects, but no public quantitative test results. Lim [8] used the mechanical and
electrical impedance (EMI) technology to monitor the three stages of fatigue crack, this technology used
the PZT material as the exciting and vibration sensor, and can monitor fatigue cracks at high sensitivity
and high precision, but can’t quantify and visualize the position of the crack. Hughes [9] found that the
detection frequency of the probe was close to its resonant frequency, which can effectively improve the
detection sensitivity of eddy current testing. Xie [10] developed a new type of flexible planar eddy
current sensor array to detect the micro crack length of the key parts of the aircraft. It can measure the
fatigue crack length quantitatively, and the detection precision can reach to less than 0.2mm. Li [11]
proposed an annular eddy current array sensor crack monitoring scheme, which can implement
quantitative monitoring of cracks. This method can improve the detection sensitivity of the sensor, but
it has limitations on the quantitative discrimination of the deeper defects and defects on the near surface.

Studies [13, 14] describe a method to assess the degree of destruction of equipment made of steel.
This type of steel is low-alloy, which makes it possible to use an electromagnetic method of control
based on the operation of a pass-through or a detachable eddy current probe.

The eddy current method is often used to evaluate various steel parameters. The possibility of using
the eddy current method for detecting defects in steels is described in the study. For more precise
positioning of the probe, a special system with the ability to control the probe in 0.1 mm increments is
used. The advantage of the eddy current method is that this method allows us to diagnose the conductive
material covered with paint and other non-conductive products.

The task of the research was to demonstrate a way to analyze the steel-paper transitions, which makes
it possible to study the surface of steel. There is a need to determine the nature of the voltage drop added
to the measuring coil of the probe during its distance from the controlled object and find out the reasons
for the obtained regularities. Of interest is the nature of the increase in voltage added to the measuring
coil of the probe when it approaches the object of study. When representing the change in the added
voltage as a mathematical dependency, we can conclude about the interaction of the electromagnetic
field created by the eddy current probe and the residual magnetic field of the steel.

The main objective of this research is to develop, study, optimize and test the superminiature eddy
current probe on samples made of electrical steel.
The main task of the study was to obtain dependencies that make it possible to draw a conclusion about the influence of various parameters of the sensor and the steel under study on the ECP signal.

2. Materials and method
To measure the voltage waveform of the ECP at the boundary of the dielectric and the conducting ferromagnetic space, an installation based on the ECP [15,16] and a digital displacement transducer was used.

The ECP of a transformer type consisted of three coils and a magnetic core placed inside a cylindrical platform. Tracks were carved on the outside of the platform. They were intended for coils, which were impregnated with the compound at 200°C after winding. This procedure made it possible to avoid the destruction of coils during the application of the ferrite shield, which was used to localize the electromagnetic field on the controlled object. The outer side of the ECP was encased with a special corundum washer to avoid contact of the core with the object of study.

The parameters of the developed ECP allow maximum concentration of the magnetic field on a certain area with dimensions of about 2500 µm² and achieve the field penetration to a significant depth of the object of study, implementing operation at a sufficiently low frequency [16].

3. Results and discussion
The experiment was conducted on two materials located at a distance of 1 cm from each other. All measurements with scanning were taken of electrical steel 1212 (sample 1), and then, through a dielectric (paper), of steel 3414 (sample 2). The frequency of the signal that is sent to the exciting coil of the ECP ranged from 2000 to 20000 Hz. The measured parameter was the voltage added to the measuring coil of the ECP during its movement relative to the initial scanning point. All the movements of the probe were controlled by the DSP. The data was digitized using an ADC and transmitted online to a program that also managed the measurement system. The data was analyzed using the Origin mathematical software.

The added voltage was measured continuously (the ECP movement at a given speed of 1 mm/s), as well as discretely (the ECP change was 0.1 mm per step, the step measuring was 0.5 s). This method of measurement is due to the characteristics of the developed software package (the ADC sampling frequency, as well as the speed of the DSP) and proved to be quite effective in the study.

In order to study the drop in the added voltage at the steel-paper boundary thoroughly, it was necessary to plot the amplitude that adds voltage versus the probe position. This dependency shows the nature of the change in the added voltage amplitude during the movement of the ECP. Measurements started at a distance of 7 mm from the edge of the first sample and continued to a distance of 7 mm from the edge of the second sample. Similarly, the ferromagnetic-dielectric interface was observed. A graph showing the dependency of the added voltage on the probe position illustrates the effect that occurs at the boundary. All results are shown in Figure 1.

The difference in peaks on the graph directly depends on the magnetic permeability of the electrical steel. According to the graph, the signal amplitude decreases sharply in the region of the paper, changing the value from 6200 mV to 2500 mV, and then drops to zero. In order to study the causes of the drop in the voltage at the steel-paper boundary in more detail, a discrete dependency of the added voltage amplitude on the position of the probe was plotted. All measurements were made at points located at 0.1 mm from each other (Figure 2).
Figure 1. Dependency shows the nature of the change in the added voltage amplitude during the movement of the ECP (2000 Hz, continuously scanning).

Figure 2. Dependency shows the nature of the change in the added voltage amplitude during the movement of the ECP (2000 Hz, discrete scanning).

According to the results of this study, the amplitude does not drop to zero at the interface of the ferromagnet but decreases according to the quadratic law. The minimum value of the signal amplitude was 59 mV. The signal amplitude increases exponentially as the probe approaches the second sample.

This dependence occurs as a result of the residual voltage in the measuring coil of the ECP. The magnetic field of electrical steel has closed lines of force. Thus, the generated by eddy currents electromagnetic field, which prevents the occurrence of self-induction in the measuring coil, cannot greatly affect the added voltage. The response value, in its turn, will not decrease to zero since the first ferromagnet continues to influence the probe.

This effect of the ferromagnet on the probe occurs because the steel has a proper magnetic field. It closes on the probe even if it is located at a great distance from it. The signal amplitude value is much smaller than the amplitude of the ECP signal when it is located directly above the metal. This voltage continues to decrease as the distance between the probe and the object under study increases.
The approach to the second sample causes the amplitude of the added voltage to increase. The magnetic fields of the first and second samples affect the probe. The addition of EMF from the fields of both samples causes an exponential increase in the amplitude.

The following experiment was performed to evaluate the influence of the frequency of the signal sent by the exciting coil of the eddy current probe on the measurement result. The dependency of the added voltage amplitude of the probe position was plotted. This dependency demonstrates the change in the amplitude of the added voltage during the change of the probe location at a frequency of 20000 Hz (Figure 3).

Figure 3. Dependency shows the nature of the change in the added voltage amplitude during the movement of the ECP (20000 Hz, continuously scanning)

The graph shows that the general nature of the added voltage dependency does not change. There are also two main peaks of the amplitude that correspond to two types of steel and a decrease in the amplitude in the paper region. It also shows a change in the rate of the added voltage drop and a changed minimum value of this voltage (5 mV). It corresponds to the moment when the probe passes through the center of the paper. Such changes occur since the magnetic losses in steel rise due to an increase in the ECP current frequency up to 20000 Hz.

In this case, the magnetic field of both samples influences the added voltage less, than at 2000 Hz. Figure 4 shows that the reduction of the added voltage in region 1 proceeds exponentially. In region 2, the amplitude increases in the same way.
Figure 4. Dependency shows the nature of the change in the added voltage amplitude during the movement of the ECP (20000 Hz, discrete scanning)

In the last experiment, the effect of the gap between the ECP and electrical steel was considered. In this study, sample 1 was scanned. The gap increased by 0.1 mm, and the measurement itself was performed at a frequency of 2000 Hz. The result is shown in Figure 5.

In this dependency, it is clearly seen that when the probe moves away from the object of study, the added voltage also decreases exponentially. The reason is that the electromagnetic field penetration depth of the exciting coil of the probe is too small to generate a sufficiently strong counterfield of the ferromagnet, which can affect the signal amplitude of the measuring coil of the probe. Besides, as the distance between the ECP and the object of study increases, the effect of the magnetic lines of steel on the ECP coil gets weaker.

Figure 5. Dependency shows the effect of the gap between the ECP and electrical steel
4. Conclusions
A special measuring system based on a superminiature eddy current probe was developed to measure the characteristics of electromagnetic steel. The experiments carried out demonstrate the possibility of its application for scanning transitions between different types of steel. The presented study helped to analyze the interaction of the magnetic field of the ECP and the residual magnetic field of steel.

The obtained regularities reflect the change in voltage when scanning the transitions of steel when implementing a circuit with different frequencies of the ECP. When the signal frequency of the ECP changes, it is possible to study the controlled object at different depths. To do this, it was necessary to evaluate the penetration depth of the magnetic field of the ECP in different steel grades and the influence of the signal frequency on the ECP response. Besides, a mathematical dependency was established describing the change in the applied voltage during the change in the gap. Thus, there is a prospect of using the developed system for scanning materials with a non-conductive coating, such as paint.

Such studies allow us to conclude about the state of the object of study by the rate and nature of changes in the applied voltage of the ECP and show the possibility of using this system in thickness measurement, as well as in the study of steel properties.

This eddy current probe can be used for evaluating and monitoring the condition of parts and units in mechanical engineering.

References
[1] Aibangbee J O and Onohaebi O 2018 Amer. J. Eng. Res. 7(1) 113-119
[2] Zhang Y and Gong Y 2020 IOP Conf. Ser.: Earth and Env. Sci. 512
[3] Marinov S G 1986 Proc. Review of Progress in Quantitative NDE vol 5 (New York) p 225
[4] Taniguchia T, Nakamura K and Yamada S 2001 International Journal of Applied Electromagnetics and Mechanics 14 503-506
[5] He Y B and Shao Y G 2010 Sensor and micro system 29(2) 80-82
[6] Liu B, Luo F L and Hou L J 2011 Journal of instrumentation 32(3) 654-659
[7] Marchand B, Decitre J M and Sergeeva C 2012 Proc. of the 39th Annual Review of Progress in Quantitative Nondestructive Evaluation (Denver: USA) p 488
[8] Lim Y Y and Soh C K 2014 Research in Nondestructive Evaluatio 25(2) 82–98
[9] Hughes R, Fan Y and Dixon S 2014 NDT&International 66(3) 82-89
[10] Xie R F, Chen D X and Pan M C 2015 Sensors 15(12) 32138-32151
[11] Li P Y, Li C and He Y T 2016 Sensors and Actuators A: Physical 246 129-139
[12] Z G Wang, B Yang, M D Li, W Zhai, S H Zhang and B Hu 2018 IOP Conf. Series: Materials Science and Engineering 439 042007
[13] Ghoni R and Dollah M 2015 Adv. in Mech. Eng. 6 1-11
[14] Almeida G and Gonzalez J 2013 Procedia CIRP 7 359-364
[15] Sagalakov A M 2017 Welding International 31(8) 608
[16] Sagalakov A M 2015 IOP Conf., Ser.: Mater. Sci. Eng. 71