Research of Steel-dielectric Transition Using Subminiature Eddy-current Transducer

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Abstract. The research aims to develop a subminiature transducer for electrical steel investigation. The authors determined the capability to study steel characteristics at different depths based on variations of eddy-current transducer amplitude at the steel-dielectric boundary. A subminiature transformer-type transducer was designed, which enables to perform local investigations of ferromagnetic materials using an eddy-current method based on local studies of the steel electrical conductivity. Having the designed transducer as a basis, a hardware-software complex was built to perform experimental studies of steel at the interface boundary. Test results are reported for a specimen with continuous and discrete measurements taken at different frequencies. The article provides the key technical information about the eddy current transformer used and describes the methodology of measurements that makes it possible to control steel to dielectric transition.

1. Introduction

The majority of industrial components failures take place due to material fatigue that frequently occurs without early enough warning. Many ferromagnetic components are subjected to alternating load in service, which often causes their structural failure as a result of fatigue [1–3]. Evidently, any improvement in the regular, economic, and timely non-destructive monitoring of the fatigue damage of critical parts of industrial construction makes an important, actual, and challenging issue. In order to check on the health of the construction materials, it is necessary to be able to detect the initiation and the early stages of the propagation of fatigue cracks, and to predict the residual lifetime of the constructions with a satisfactory timeliness of the forecast.

Over the past century, many non-destructive methods have been studied in research on fatigue damage evaluation. Some of the methods that showed promise for metals and alloys included x-ray diffraction, (see e.g. [4]), laser diffraction [5], infrared thermography [6] and positron annihilation [7]. At present, non-destructive test methods for detecting fatigue cracks, such as the ultrasonic test, eddy current inspection and penetrant inspection, etc., can only find macro-defects of certain sizes. These methods are unsuitable for early warning of approaching fatigue damage [8, 9]. As a dynamic detection method, acoustic emission can diagnose early failure, but has some limitations in wide applications. For example, measurements using this method must be performed under loading conditions, and measured signals are difficult to analyze due to interference by noise [10, 11].

Magnetic measurements are frequently used for the characterization of changes in ferromagnetic materials, because magnetization processes are closely related to their microstructure. This makes the
magnetic approach an obvious candidate for non-destructive testing and for the detection and characterization of any defects in materials and in products made of such materials [12]. The magnetic non-destructive evaluation of the fatigue damage of ferromagnetic steels was reported in [13]. One of the most frequently and successfully used methods is the traditional hysteresis method. A number of techniques have been suggested, developed, and are currently used in industry, (see e.g. [14, 15]).

The primary advantages of these sensors are generally summarized as being small in size, with simple design, ease of preparation, low cost, good metrological characteristics and a lack of necessity for a permanent connection of complex measuring and recording instruments. On the other hand, the common drawbacks for the application of these fatigue damage sensors in actual products are high environmental sensitivity, low stability, low reliability, as well as low repeatability.

An eddy-current method is also proved [16, 17] effective for investigation on physico-mechanical properties of steel. This method is a widely used means of non-destructive testing based on analyzing interaction between external electromagnetic field and eddy currents introduced by this field.

The works [18-20] suggest the method for brittle fracture evaluation in metal equipment made of 09G2S low-alloy steel by means of the electromagnetic control method with the use of transmission gages and attachable gages.

The eddy-current control method is often used for evaluation of various steel parameters. The investigations [21, 22] demonstrated practicality of using such method for fault location in AISI 304 steels. At the same time, the developed gage positioning system with the pitch of 0.1 mm was used for accurate gage movement. The work [23] highlights that one of the obvious advantages of using eddy-current method for investigation of conductive materials is its applicability for diagnostic of materials with paint and varnish, and other non-conductive coatings.

The research is aimed at development, investigation, optimization and testing of microminiature eddy-current transducer for steel analysis. An important task within the research is to obtain dependences describing the range of response of the eddy-current transducer to the change of its parameters and physico-mechanical properties of the studied steels.

2. Materials and Methods

A unit based on an eddy-current transducer (ECC) [24-25] and a digital displacement transducer (DDT) was used for measuring stress-strain behavior on the boundary of dielectric and conductive ferromagnetic space.

The eddy-current transducer represents a transformer with measuring, transmitting and compensation coils and a coil flux guide located inside a cylindrical platform. Grooves are arranged on the external side of the platform to locate the coils impregnated with compound at the temperature of 200 °C. This prevents destruction when applying ferrite screen meant for localization of electromagnetic field on the test object. On the exterior, ECC is put into alumina bead which protects the core from contacting with the test object.

Parameters of the designed ECC allow effectively localizing magnetic field within the area of 2500 mkm² and provide its considerable penetration deep into the test object when operating at low frequencies [25].

The digital signal from the virtual generator is sent to the input of the digital–analog converter of the sound card. The analog signal then passes through a power amplifier to the exciting winding of the eddy current transformer. The sinusoidal signal creates an electromagnetic field, which, on interacting with the sample, induces an emf in the measuring winding of the eddy-current transformer. This voltage is sent through a preamp to the microphone input of the sound card and then to the input of the analog–digital converter in the sound card. The resulting digital signal is sent to the analysis and control module of the software. This module determines the magnitude of the digital signal (in conventional units) corresponding to the introduced voltage at the measuring winding. The computer’s sound card permits variation in frequency of the electromagnetic field created by the exciting winding within the range of 100–10000 Hz in the course of scanning.
Experimental study was performed using two materials located with a 1 cm gap between each other. Scanning measurements were initially taken in electric steel of type 1212 (specimen No.1) through a dielectric (paper), and then in steel of type 3414 (specimen No.2). Frequency of the signal transmitted to the transmitting coil of the ECC varied within the range of 1000-10000 Hz. The measurable parameter was voltage introduced in the measuring coil of the ECC in the process of its displacement from the initial scanning point. The transducer displacement was measured using a digital displacement transducer (DDT). The data were digitalized with the help of an ADC and then in real-time mode were transmitted to the software that controls the measuring system. Origin math tool was used for data analysis.

The introduced voltage was measured both continuously by moving the DDT with the constant velocity of 1 mm/s, and discretely by moving the DDT with the pitch of 0.1 mm and time of 0.5 s for each pitch.

3. Experimental results
For the purpose of detailed study of introduced voltage on the ferromagnetic-dielectric boundary, a dependence curve of introduced voltage amplitude on the gage position was obtained. This curve demonstrates the behavior of introduced voltage amplitude variation while moving the ECC above the steel-dielectric boundary. The variations were observed starting from the point located 5 mm away from the edge of the first specimen up to the point corresponding to the distance of 5 mm from the edge of the second specimen. This way, one can observe ferromagnetic-dielectric interface which is qualitatively related to the distance up to and beyond the edge of the test object. The dependence curve of introduced voltage amplitude on the gage position explicitly demonstrates the effects occurring on the interface. The experimental results are presented in Figure 1.

![Figure 1. Dependence curve of introduced voltage on the gage position while continuous scanning at 1000 Hz.](image)

Difference of peaks of the curves depends on the permeability of electric steel. The curve demonstrates that in the dielectric area, the introduced voltage drops from 6000 mV to 2000 mV and then smoothly tends to zero. For more detailed study of introduced voltage drop on the ferromagnetic-dielectric boundary, a curve for discrete dependence of introduced voltage amplitude on the gage position was obtained (Figure 2). Discrete scanning of objects was planned within the experiment. Measurements were performed in points located at 0.1 mm from each other.

As a result of the experiment the following conclusion can be drawn: on the interface, ferromagnetic response does not drop to zero value, but decreases according to square law (area 1). The minimum value of introduced voltage amplitude is 50 mV. An increase of the signal amplitude
when approaching the second steel specimen occurs according to a law similar to exponential one (area 2).

Figure 2. Dependence curve of introduced voltage amplitude on the gage position while discrete scanning at 1000 Hz.

Such dependence can be explained by residual voltage in coils of ECC. Continuous field lines are distinguished in the field of electric steel. Therefore, electromagnetic field that prevents occurrence of self-inductance in the measuring coil and is generated by eddy currents will have little effect on introduced voltage. At the same time, the response value will not drop to zero due to ferromagnetic influence on the gage.

Such influence is explained by presence of self-magnetic field of steel which is closed on the ECC even at relatively big distance. In this case, the value of introduced voltage is considerably lower than the value of voltage introduced in the transducer when positioning the gage right above the steel specimen. This voltage keeps reducing with the increase of distance between the gage and the test object.

When approaching the second specimen, introduced voltage amplitude increases. In such case, magnetic fields of the first and the second specimens affect the gage simultaneously. Exponential growth of introduced voltage amplitude is caused by adding electromotive forces (EMF) of both specimens' fields.

Another experiment was performed to assess the effect of ECC signal frequency on measurement results. The dependence curve of introduced voltage amplitude on the gage position was obtained, which demonstrated variation of the amplitude when moving the gage at the frequency of 10000 Hz. The experimental results are presented in Figure 3.
The curve shows that the gage position has almost no effect on qualitative dependence of ECC introduced voltage. The two peaks of introduced voltage correspond to two types of studied steel. Drop of introduced voltage is caused by dielectric which separates the two specimens. One can well notice the varied rate of introduced voltage drop and the minimum value of introduced voltage (5 mV) which corresponds to the moment when the gage comes through the dielectric. Such dependence can be explained by increased magnetic loss in steel with the increase of current frequency in the ECC up to 10000 Hz.

At a given frequency, the magnetic field of the steel has a significantly lower influence on applied voltage than in the case corresponding to 1000 Hz. It is shown in Figure 4 that drop in applied voltage in area 1 occurs exponentially, unlike Figure 2. Voltage increase in area 2 also occurs exponentially.

4. Conclusion
As a result of the research, a measurement system for electric steel parameters is developed. The investigation revealed practicability of scanning steel to dielectric transition using an eddy-current
transducer. Obtained measurement data allowed describing interaction between magnetic field of ECC and residual magnetic field of steel.

In addition, mathematical functions were obtained to describe variation of introduced voltage while scanning similar transitions at various ECC signal frequencies. Changing ECC signal frequency enables one to investigate test objects at various depths, but it is required to establish unique dependence between the ECC response and the penetration depth of ECC magnetic field into various types of steel.

Based on the conducted research, a certain conclusion can be made on the state of the studied object with regard to behavior of ECC introduced voltage variation. The investigation also proves that the measurement system is appropriate for thickness measurement and for studying structural properties of steel. Further extension of the method will allow assessing quality of studied material by its comparison with check specimens of corresponding types of steel.

The presented eddy-current transducer for structural materials investigation can be used for diagnostic and control of critical joints and structural machine elements used in electrical engineering.

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