Control properties of steel by using subminiature eddy current transducers

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Abstract. In the course of study, various properties of materials were determined using the developed measuring system. The study was conducted on pipes made of high-strength steel 08G2B, the strength category of which belongs to the K65 group. The type of high-strength steel 08G2B belongs to the category of steel with an ultralow carbon content, which makes it possible to study the properties of this material using the eddy current method. A miniature eddy current probe was used for the study. The probe consisted of a core and three coils. The core material is alloy 81NMA. The main parameter of the measurement system, which provides basic information about the object of control, is the signal given by the measuring coil of the eddy current probe. The study was based on samples with integrity defects such as cracks and holes. Besides, the results of the study simulating corrosion in the metal are described.

1. Introduction

The volume of construction using various pipelines has been growing up in recent years. Plate steel 08G2B with an ultralow carbon content is increasingly used for their construction. It is extra strong due to its fine-grained structure, which is obtained as a result of controlled rolling, accelerated cooling, alloying and balancing of strengthening mechanisms. This type of steel belongs to the strength group K65 (X80). The main advantage of this type of steel is the stability of its functional properties. This guarantees the safety of engineering structures operation.

Unfortunately, this type of high-strength steel, due to its composition and manufacturing technology, is frequently subject to destruction, especially in high-rise buildings. Hot rolling further accelerated cooling and the use of ultrafine grain with high density makes it susceptible to destruction, especially at high loads.

Now, many measures are being taken that will help to identify peculiarities of the destruction of this type of steel under high pressure. New methods are being developed to evaluate the properties of steel more properly and determine its quality and the possibility to resist destruction.

The influence of low mechanical properties of steel on the occurrence of cracks and various defects is poorly studied. In this regard, the creation of new ways to study steel is quite relevant.

One of the most important spheres of high-strength steel application in civil engineering, in which pipeline systems are made from it. The main problem is reliability and trouble-free operation of the steel pipeline since the metal undergoes natural ageing during operation. Failures in the pipeline are
caused by the presence of corrosion and natural metal fatigue. According to statistics, about 29 per cent of the revealed defects in pipelines were defected due to external corrosion.

The practice of using the existing testing methods shows their low sensitivity to defects in the pipe metal. Now, the sensitivity of defect scores can detect cracks that are more than 10% of the diameter of the pipe itself. Thus, cracks up to 2 mm deep in pipes with a diameter of 1400 mm, which are most in-demand, are not detected. This process leads to an increased risk of structural failure.

For evaluating and inspecting defects in metallic materials, many types of nondestructive testing (NDT) methods exist, including magnetic testing, ultrasonic testing, and X-ray testing. The eddy current test is a magnetic testing method widely used for detecting surface cracks in metal structures [1, 2].

Electromagnetic methods (including the eddy current) have the greatest susceptibility to defects on the surface of high-strength steel. Such testing methods help to provide convenience, and most importantly, fast control, and allow determining the depth of defects. Hence, a decision is made about the condition of a particular pipe section.

A typical eddy current transducer (ECT) uses a pair of coils, namely, a detection coil and an induction coil. The detection coil measures the secondary magnetic field of the eddy current in the metal; this magnetic field is caused by an ac applied magnetic field from the induction coil. In the case of a nonmagnetic metal, ECT using a detection coil is sufficient to detect an abnormal eddy current distribution caused by a flaw because the applied magnetic field originates from the eddy current. However, the ECT method is sometimes difficult to apply to ferromagnetic materials because the applied magnetic field is composed of both the eddy current and magnetization signal. Therefore, the magnetization signal becomes problematic, creating a detection error called magnetic noise.

Another magnetic NDT method to minimize the influence of the magnetized fluctuation, while detecting a surface flaw in ferromagnetic materials, is the magnetic flux leakage (MFL) test. MFL detects a leaked magnetic flux above a crack when a magnetic field is induced by the electromagnetic yoke at the part separated from the crack position. For reducing the influence of magnetization, a strong applied magnetic field is operated in or near the saturation region in the M–H curves. Consequently, conventional MFL equipment requires a high-power current source to generate a strong applied magnetic field [3-4].

Recently, a magnetic sensor was used for replacing the detection coil in magnetic NDT [5-8]. Compared to ECT, MFL has an improved detection performance at not only the surface but also the subsurface. However, MFL requires a large sensor probe owing to the configuration of the separated magnetic yoke and sensor position. For detecting a surface flaw, the small size of an ECT is advantageous as it can be used for measuring a small or a complicated nonplanar shape [9].

The signal detected through the sensor contains different types of information, such as the frequency response characteristic and localized detection performance. We developed an ECT method that uses the system for suppression of noise and amplification of the signal to resolve the magnetic noise problem in ferromagnetic materials.

The eddy current method is also suitable for testing pipes, since the pipeline is rough, and often has different insulation or protective coatings. Thus, defects can only be revealed using eddy current testing.

The primary purpose of this study is to determine the relationship between eddy current probe signals and the properties (mechanical and operating) of steel of the strength grade K65 and demonstrate the probe abilities to detect integrity defects and corrosion of high-strength steel.

2. Material choices and design
Steel pipes 08G2B with various defects were chosen for the study. Cracks were simulated to recreate integrity defects, and the method of drilling holes at various depth was used for imitating corrosion.

The eddy current probe was used for testing. It consists of a magnetic core made of permalloy 81NMA in the shape of a pyramid. Three coils (exciting, measuring, and stabilizing) were wound on
the magnetic core. All types of coils were impregnated with an epoxy compound and formed a monolithic structure.

The degree of defectiveness was estimated by comparing the recorded ECT signal amplitude decaying as compared with the signal amplitude when scanning the defect-free part of the test object.

The main parameters of the developed eddy-current differential transducer:
- The excitation frequencies: 500 Hz, 2000 Hz, 5000 Hz.
- The excitation winding internal diameter: 0.25 mm
- Measuring winding internal diameter: 0.1 mm
- Coil spacing: 0.15 mm
- Number of excitation winding turns: 80
- Number of measuring winding turns: 400

The transducer contained a compensating winding with an opposite connection to the measuring winding. Due to such connection circuit, the output signal of the transducer is equal to zero in the absence of a test object near the sensor.

The developed measuring system circuit operates as follows: based on the Arduino microcontroller, a generator is built that generates a special signal in the form of a sine wave, the parameters of which (frequency and amplitude) are set using software installed on the computer. This signal passes through a special power amplifier built on a TDA 7267 chip with unipolar power supply. After passing the amplifier, the sine signal enters the exciting coil of the ECP. Then, the magnetic field created by the exciting coil enters the material and creates a counter field of eddy currents, which is received by the measuring coil. This counter field carries all the necessary information about the defects of the controlled object. The measuring coil in its turn is connected to the upper and lower frequency filters through which the signal passes. In this case, the filtering and generation frequencies are controlled synchronously to clear the signals from interference. After filtering is performed, the signal is recorded by a personal computer, entering the amplitude detector.

3. Experimental results

3.1. Sample 1.
The sample was a steel pipe with milled cracks. The pipe thickness was 8 mm. For the experiment, cracks were made at a depth of 1, 3, 5 mm. The crack opening was 2 mm. The current frequency on the exciting coil was 500 Hz.

The signal amplitude depends on the location of the probe above the object of control: its change when the probe passes over the object indicates spots where defects are located (Figure 1).
Figure 1. Results of the study of a metal pipe at a frequency of 500 Hz (crack).

Point 1 indicates a crack at a depth of 2 mm, point two at a depth of 3 mm, point 3 at a depth of 5 mm, respectively. It is seen that with such defects, the signal amplitude begins to decrease when approaching the location of the crack. The minimum amplitude value corresponds to the area in the middle of the crack in the steel, which means that the location of the crack can be identified. For example, the change in the amplitude of the ECP signal, depending on the location of the probe relative to crack 1, is described by the formula: \( U = 0.578x + 0.00323x^2 \).

The depth of the crack location can be determined by changing the operating frequency of the ECP. Figure 2 shows the results of the study of a metal pipe at a frequency of 2000 Hz (line 1) and 5000 Hz (line 2).

Figure 2. Results of the study of a metal pipe at a frequency of 2000 Hz(1) and 5000 Hz(2).
Each line shows defects: on line 1 two out of three, on line 2 one out of three. If we calculate the depth to which eddy currents penetrate, we can use the results of this experiment to determine the depth at which the crack is located.

3.2. Sample 2

The sample was a pipe with three holes drilled at a depth of 3 mm. The diameter of holes was 1, 3 and 5 mm. A signal amplitude change may indicate the location of defects during the probe movement over the studied object (Figure 3).

![Figure 3. Results of the study of a metal pipe at a frequency of 500 Hz (hole).](image)

However, compared to the signal sent by the probe while scanning holes, a steeper amplitude decrease can be noticed when the probe approaches the defect. The dependence of the amplitude on the ECP signal relative to the first drilled hole is described by the function: \[ U = 0.778x + 0.052x^2. \]

When scanning pipelines, a situation is often observed when the surface of the scanned area is covered with a layer of non-conductive paint coating. During the second experiment, a polyethylene layer 0.1-0.5 mm thick was placed over the sample in order to determine the effect of the nonconducting layer on the ECT signal amplitude. The measurement results for a defect with a diameter of 1, 3 mm drilled at a depth of 3 mm are presented in Figure 4.
**Figure 4.** Dependence between the eddy-current transducer signal and defects of 1, 3 mm drilled at a depth of 3 mm on the gap.

These figures demonstrate low dependence of the signal amplitude on the gap to a drilling depth of 2.6 mm, which is about 50 per cent of the total pipe thickness. As compared with Figure 3, the changes in signal amplitude were about 12%. As the drilling depth increased and, as a consequence, the defect got closer to the test item surface, the influence of the nonconducting layer on the ECT signal also increased. At a drilling depth of 2.6 mm, the deviation of the maximum change in the signal amplitude was about 60% as compared with the results presented in Figure 3.

4. Conclusions
The results obtained from laboratory tests of the automated measuring system showed the effectiveness of the developed system for steel pipelines quality control and its high sensitivity to various integrity defects such as stress-corrosion cracks and metal corrosion. The informative value of the eddy current probe signal is demonstrated when scanning integrity defects such as cracks and various holes in a steel pipe. The eddy current probe signals from various defects change at a different speed, which gives us an idea of the type of defect.

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