The steel defects investigation by the Eddy current method

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Abstract. The paper describes the gage system designed for the various properties materials study. Within the study frameworks, the sections of pipes made of a new material — high-strength steel 08G2B of K65 steel grade were studied. These materials are ultra-low-carbon steels, wherefore it is possible to study their properties using the eddy current method. A subminiature eddy current transducer consisting of three windings on a core made of 81NMA alloy was used during the study. The resulting parameter of the gage system, which contains information on the object under study, was the change in the eddy current transducer signal. In this study, the samples with continuity defect models — cracks and holes — were investigated, and a study was conducted to simulate the corrosion presence in the metal.

Introduction

In recent years, hot-rolled heavy plates of high-strength ultra-low-carbon steel 08G2B are used increasingly for the construction of fuel lines, buildings, ships, etc. Due to the ultra-fine grain structure obtained as a result of controlled rolling with accelerated cooling application, alloying and balanced hardening mechanisms, steel grades K65 (X80) are of high structural strength. The key point when using steel is its properties stability to ensure reliable, trouble-free building structures operation.

However, modern high-strength construction steels, due to the heavy plates production technology (accelerated cooling of hot rolled products) ultra-fine grains with increased dislocation density, are the subject to destruction under high loads that may appear for example in high rise buildings, etc.

To date, many efforts have been made to study the destruction high-strength steels characteristics at high loads and develop more correct methods for assessing the steel properties, allowing to determine its quality and the ability to resist fracture.

The high-strength steel new types research is also necessitated to evaluate the mechanical welded joints properties of such materials. Despite the significant improvements in welding technology in recent years, mechanical properties of welded joints are still much worse than base metal. The applied welding technologies a priori do not provide the properties comparable to the base metal. The situation worsens by the fact that the weld in any metal has heterogeneous properties and is a stress concentrator. This is the source of nucleation, growth and propagation of cracks in the weld. The welds low mechanical properties are the reason that the strength characteristics of the whole structure will be determined by the weld properties, as the weld is the weakest part of the whole structure. At the same time, the welded joints low mechanical properties influence issues on initiation and development of cracks are not well studied, which makes the task of studying this problem relevant.
One of the current fields of high-strength steel use in construction is pipelines for various applications (main pipelines, process pipelines, etc.). The problems of ensuring the reliability and steel pipelines fail-safety due to their susceptibility to normal aging is very serious.

Generally, pipelines failures are caused by corrosion and mechanical fatigue of metal. According to statistics, 29 percent of defects in high-strength steel pipes are continuity defects such as external corrosion.

During the steel pipes use, a variety of non-destructive tests are performed [1]. Ultrasound and X-ray methods are used most commonly. Magnetic particle method is often performed, e.g. to inspect the pipe ends.

Existing non-destructive testing methods demonstrate their insufficient sensitivity to pipe metal defects. According to the study [2], the sensitivity of currently used crack detectors allows to detect cracks with depths of more than 10% of the pipe wall thickness, therefore cracks of up to 2 mm deep cannot be detected in the most standard pipes with a diameter of 1,400 mm, as a result there is a risk of high failure rate of a structure.

Electromagnetic (e.g. eddy current) testing methods are most sensitive to high-strength steel surface defects. Such inspection methods provide quick and convenient testing, determine the crack depth and allow to consider the pipeline section state tested.

Additionally, by reference to practical experience, in conditions of increased roughness or after applying an insulating or protective coating on the metal, it becomes possible to detect defects in steel or a weld using the eddy current method (ECM).

Eddy current testing methods have been developed as the main technique for pipe inspection. They can also be utilized to identify interior corrosion resulting from metal deficits. The eddy current inspection has various features that make it an appropriate option for pipe inspection purposes. Most importantly eddy current sensors do not require any mechanical contact between the ECM probe and the test object [3].

ECM technique can detect surface and near-surface flaws in ferromagnetic components. However, the use of MFL technique is limited for detection of localized and sub-surface flaws due to its poor sensitivity to feeble leakage magnetic fields from such flaws.

Several types of highly sensitive ECT sensors have been developed by the researchers [4–8] to improve the capability of the technique. Park et al. [4] developed a sensor system using eddy-current method for detecting small depth flaws in an 8 in. diameter pipes. They showed that the sensor system could increase the sensitivity by 200%. Ravi Kumar et al. [5] developed microsensors for detection of flaws in a 12 mm thick carbon steel plate. They observed that micro-sensor showed improved performance in terms of sensitivity and wide linear response compared to the conventional sensors. Gruger [6] developed miniaturized sensors array for NDT applications and reported the detection of 2 mm diameter holes in a 1.5 mm thick steel sheet (Yashan et al.) [7] used ECT sensors to detect small inclusions in thin steel sheets by the MFL technique (Sharatchandra et al.) [8] used ECT sensor to detect localized flaw and loss of metallic area in a 64 mm diameter track rope used in mining industries. Commercially available ECT instruments consist of permanent magnets for magnetization and pickup coils or Hall sensors for measuring the leakage magnetic fields [9–11]. These instruments have limitations for detection of localized and sub-surface flaws. Also, commercial ECT instruments cannot be used for detection of flaws in small diameter (inner diameter, ID < 15 mm) tubes due to their probe size. The detection of localized and sub-surface (outer diameter, OD) flaws in small diameter tubes demand the use of high-sensitivity ECT instrument to capture the information from feeble magnetic fields associated with these types of flaws.

The purpose of this study is to determine dependency of eddy current sensor signal and mechanical and operational properties of the base metal (K65 steel grade) and demonstrate the developed eddy current transducer ability to detect continuity defects and corrosion in this type of metal.

Materials and methods
Steel pipes with model defects were used as an object of research. The pipes were made of high strength steel 08G2B. Continuity defects were simulated in the form of cracks, pinprick-like corrosion was made by drilling metal to different depths. 

In accordance with the paper [12-14], the following design of the eddy current transducer was constructed:

The design of the eddy current transducer used to test steel pipes was a magnetic core made of permalloy 81NMA in the shape of a pyramid. The energizing winding, measuring winding and compensating winding were wound on the magnetic core. The winding turns were impregnated with epoxy compound to form monolithic structure.

Operational scheme of the developed gage system is as follows: generator on the basis of Arduino microcontroller generates a sinusoidal signal. The frequency and amplitude of this signal is set using software installed on PC. The signal passes through a power amplifier made on the basis of TDA7267 circuit with single-supply operation. After the power amplifier, the signal is transmitted to the energizing winding of the eddy current transducer. The magnetic field of the energizing winding penetrates the tested material and induces an eddy current counter field detected by the measuring winding. This counter field allows to receive information about defects of the inspected object. The measuring winding is connected to several low- and high-pass filters, and the filtering frequency is controlled synchronously with the generation frequency in order to eliminate the interference. After filtering, the signal is transmitted to the amplitude detector and recorded by the PC.

**Experimental results**

Sample No. 1 was a steel pipe with milled cracks. The pipe wall thickness was 8 mm. The cracks were located at a depth of 1 mm, 3 mm and 5 mm (Figure 1). The crack width was 2 mm. The current frequency on the energizing winding was 500 Hz.

![Figure 1. Steel pipe with milled cracks](image)

The signal amplitude dependence on the transducer location above the inspected object shows the defects location via amplitude drop (Figure 2). 1 — corresponds to crack located at 1 mm depth, 2 — a crack at 3 mm depth, 3 — a crack at 5 mm depth.

We can see that the signal amplitude starts dropping before reaching the crack. Moreover, the smallest signal amplitude value corresponds to the middle of the crack in metal and allows to determine its location. For example, the ECT signal amplitude dependence on the transducer location...
relative to the first crack is described by the following polynomial: \[ U = -0.2273x^4 + 21.03x^3 - 720.34x^2 + 10820x - 59664. \]

Figure 2. Results of a pipe inspecting at frequency of 500 Hz (type defects – crack)

It is possible to determine the crack depth by changing the ECT operating frequency. Figure 3 shows the results of a pipe inspecting at frequency of 2,000 Hz (line 1) and 5,000 Hz (line 2). On the line 1 — only two of three defects are visible, on the line 2 — one defect of the three. We can use the scanning results at different frequencies to determine the cracks depth by calculating the depth of eddy currents penetration.

Sample No. 2 was a steel pipe with three drilled holes at a depth of 3 mm. The holes had a diameter of 1 mm, 3 mm and 5 mm. The signal amplitude dependence on the transducer location above the inspected object shows the defects location via signal amplitude drop (Figure 4).

At the same time, in contrast to the transducer signal received from the cracks, it can be noted that the signal amplitude drops much steeper when approaching to the defect. For example, the dependence of ECT signal amplitude on the transducer location relative to the second hole is described by the following polynomial: \[ U = 69x^2 - 4277x + 66718. \]
In the third experiment, scanning was performed with different gaps between the ECT and the metal. The gap was formed using non-conducting material consisting of several layers of paper. The total gap thickness varied from 0.2 to 2 mm (Figure 5).

The gap allowed to show the corrosion effect on the eddy current transducer signal, since the effect of this type of defect on the signal is equivalent to increasing the gap between the metal and the ECT. We can see that the increasing gap between the ECT and the defect-free metal leads to a monotonic decreasing the signal amplitude. This dependence is described by the following polynomial: 

\[ U = 0.128x + 0.657x^2 + 0.056x^3 \]

and allows to specify the corrosion layer size on the steel surface.

**Summary**

The automated gage system laboratory tests results showed its effectiveness for inspecting the steel pipelines quality and high sensitivity to continuity defects such as stress-corrosion cracks and metal corrosion. The explanatory signal value of the eddy current transducer located above continuity defects such as cracks, holes and metal corrosion in a steel pipe has been determined. Extremums of
the eddy current transducer signal above different types of defects were at different speeds that makes it possible to determine the defect type.

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