Subminiature eddy-current transducer for studying defects in weld joints of high-strength steel

A V Ishkov¹, S F Dmitriev², A O Katasonov² and V N Malikov²

¹Department of technology of construction materials and repair of machines, Altay State Agricultural University, Krasnoarmeickyi, 73, 656057, Barnaul, Russia
²Physical-technical faculties, Altai State University, Lenina, 61, 656057, Barnaul, Russia

E-mail: osys11@gmail.com

Abstract. The article describes the design of a hardware-software system intended for studying the properties of high-strength steels. Within the scope of the study, defects in the welds of the transformer tanks made of high strength 08G2B steel were being located. Such materials belong to ultra-low-carbon steels, and thus, it is possible to study their properties applying the eddy-current method. In the course of the work, a subminiature eddy-current transducer with three coils wound on a core made of 80NM3 ferrite was designed and optimized. In the work, samples with model continuity defects (cracks and holes) were examined, and a study was conducted in order to simulate weld corrosion defects.

1. Introduction

Over the last years, hot-rolled plates of high-strength ultra-low-carbon steels of 08G2B type are being increasingly used in the construction of fuel pipelines, buildings, ships, etc. Due to the ultrafine-grained structure obtained as a result of controlled rolling with accelerated cooling, alloying and balanced hardening mechanisms, the steels of K65 (X80) strength class have high structural strength. A key issue in the use of steels is the stability of their functional properties providing the reliable trouble-free operation of structures.

By now, a lot of effort has been made to study the features of the high-strength steels destruction at high pressure and develop more correct methods for steel properties assessment making it possible to determine its quality and resistance to breakage.

The study of new types of high-strength steel also led to the necessity of assessing the mechanical properties of welded joints of such materials. Despite a significant improvement in welding technologies achieved over the recent years, the mechanical properties of welded joints are still significantly lower as compared to the metal itself. The applied welding techniques are not able to provide the same level of these properties as those of the parent metal. The situation is exacerbated by the fact that any welded seam in a metal is not uniform by its properties and is a stress concentrator. It is a source of initiation, growth and propagation of cracks in the weld. The low mechanical properties determine why the strength characteristics of the whole structure will be determined by the properties of the weld, as the weakest part of the whole structure. At that, the issues of the influence of bad mechanical properties of welded joints on the problems of cracks initiation and development are poorly studied, which makes the objective of this problem studying relevant.
One of the topical areas of industrial application of high-strength steel welding is the manufacture of TMG transformer tanks. Such transformers comprise of a metal casing (tank), where the windings of aluminum or copper wire, or foil on the low voltage (LV) side are located.

The inside of the tank is filled with oil for heat removal from the windings during the operation of transformer.

The temperature fluctuations in the oil mass are being compensated, as all walls of the transformer tank are made of corrugated material which can increase and decrease in size.

Currently, the TMG transformers have a low level of no-load losses, which is topical due to the electric energy cost increase. Also, they are characterized by have a low sound power level, which corresponds to stricter environmental requirements. Such properties of TMG transformer make it low-noise, energy-saving and fast-payback equipment.

Hermetic sealing of transformers in corrugated tanks in combination with preliminary high-level degassing of transformer oil and its filling under high vacuum guarantee greater electrical insulation strength. As a result, it does not require any maintenance during storage and operation of the transformer throughout its entire service life. Accordingly, TMG transformers have increased reliability and extended service life. The enhancement of transformer reliability and extension of its service life is achieved by increasing the resistance of transformers to short circuits due to the transition to sealed transformers.

Application of new technologies and use of modern winding and insulation material made it possible to develop such a sealed transformer design where the negative effects of external short-circuit current shock are minimized, and achieve significantly less heating of the windings during operation of the equipment, as well as provided an opportunity for electric energy saving due to lower no-load current and maintenance costs.

During the operation of transformer oil tanks, a wide variety of non-destructive welded joint testing methods are used [1]. The most common methods are ultrasound and x-ray. The magnetic particle method also finds its application.

The electromagnetic (particularly, eddy-current) control methods are the most sensitive to surface continuity defects of high-strength steel. The control methods of this type make it possible to provide quick and convenient control, determine the depth of a crack, and take a decision concerning the condition of the weld being studied.

Moreover, based on practical experience, it is possible to detect defects in steel or a welded seam only using the eddy-current method under conditions of increased roughness or after applying an insulating or protective coating on the metal.

The eddy-current control method is used as the main method for controlling the steel used in TMG-series transformers. This method allows to identify internal metal corrosion damage. One of the important features of the method making it suitable for the control of transformers is the absence of a requirement of mechanical contact between the eddy-current sensor and the object of control [2, 3].

The eddy-current method is capable of detecting both surface and near-surface defects in ferromagnetic materials. However, the use of the method for the detection of extremely local defects, as well as defects located below the surface of the material is extremely limited. This is due to low sensitivity of the existing eddy-current sensors to weak distortions of the magnetic field caused by such defects.

Several types of highly sensitive eddy-current sensors are described in papers [4-8] making it possible to improve their capabilities. Park et al. [4] developed a gage system that implements the eddy-current method for detecting shallow defects in pipes with a diameter of 8 inches. They showed that using a sensor system can increase the sensitivity to defects by 200%. Ravi Kumar et al. [5] developed miniature sensors intended for defect detection in a 12-mm thick carbon steel plate. They reported that the miniature sensor showed significantly improved characteristics in terms of sensitivity and locality compared to conventional sensors. Grueger [6] developed a whole matrix of miniature eddy-current sensors for non-destructive testing and was able to detect holes with a diameter of 2 mm in a 1.5-mm thick steel sheet. Yashan et al. [7] used eddy-current sensors for localizing small defects.
in thin steel sheets applying the MFL method. Sharatchandra et al. [8] used an eddy-current sensor to detect an extremely local defect in the form of a thinning of the metal area in a crawler chain with a diameter of 64 mm used in the mining industry.

The eddy-current measuring instruments currently available on the market include permanent magnets designed to magnetize a steel sample, as well as measuring coils or Hall sensors for measuring the magnetic fields created by eddy currents [9, 10].

The main problem of devices of this class is their inability to detect local and subsurface defects. The detection of localized and subsurface defects in the walls of a transformer tank requires the use of a highly sensitive eddy-current device to collect information from the weak magnetic fields associated with these types of defects.

The purpose of the work is to determine the relationship between the signal of an eddy-current sensor and the mechanical and operational properties of the base metal of steels of K65 strength class and demonstrate the ability of the developed eddy-current transducer to find continuity and corrosion defects in this type of metal.

2. Materials and method

In order to adjust the process of welded seams of steel alloys studying followed by verification of the correctness of measurements made using the developed hardware and software complex, it is necessary to create control samples containing model defects with known parameters including the depth, size and type of the defect.

As a study object, a sample represented by an oil tank of the TMG-400/10/0.4 transformer was used. The walls of this tank were made by welding of sheet steel with a thickness of 2 mm. When welding a seam, various defects (cracks, corrosion damage) were simulated, made by metal drilling and sawing to different depths.

Figure 1 (Sample No. 1) shows a photo of a sample steel weld with defects represented by two cracks occurring at a depth of 0.5 mm and 1.5 mm, respectively.

Figure 2 (Sample No. 2) shows a photo of a sample steel weld with a defect represented by a model of a corrosion pin-hole defect.
Figure 2. Photo of a sample steel weld with a defect represented by a model of a corrosion pin-hole defect.

Figure 3 (Sample No. 3) shows a photo of a sample steel weld with a defect represented by a model faulty fusion with different weld filling degrees (30%, 60%, 90%).

For comparison, a photo of a sample steel weld without simulated defects is also shown (figure 4, Sample No. 4).

The eddy-current gaging circuit consists of a surface eddy-current transducer (ECT) including a coaxial generating inductance coil, measuring inductance coil, and also an inductance coil intended for the compensation of the effect of the generating coil magnetic field [11, 12].

The current of the generating ECT winding connected to the generator output creates a magnetic field. Due to the opposite connection of the measuring and compensating windings, the ECT signal is equal to zero in the absence of the control object near the ECT. If an electroconductive object is placed
near the measuring winding, the magnetic field of the generating winding induces eddy currents in the object, which provide the appearance of a signal carrying information about the control object.

The circuit also includes an electronic unit with a function of additional auto-compensation and quantitative indication of the signal received from the measuring winding. The recorded ECT signal is the amplitude of the electromotive force induced on the ECT measuring winding.

In the measurements performed during this study, an ECT with the generating winding of 0.5 mm and measuring winding of 0.1 mm in diameter was used. The generation current frequency was chosen subject to retention of sensitivity to the defect depth of up 2 mm and amounted to 2 kHz. The working gap between the transducer and the test object was 0.2 mm; an electroconductive aluminum plate made of aluminum foil with a thickness of 0.1 mm was used as a gap. The sample was made of St 20 steel sheet and contained various defects.

Measurements on the developed samples were taken using the designed subminiature ECT operating under the control of the VDSS-8 hardware and software complex. To register the signals received from the ECT, the electronic unit combining the transformer meter with a received signal spectrum analyzer was used making it possible to visualize the received signal represent it in a convenient form on a computer screen.

The feature of the developed hardware and software complex lied in the possibility to adjust its operation for a specific sample, thus providing the maximum efficiency of the ECT. In the course of such adjustment, the amplitude and phase data are recorded in the computing unit of the hardware and software complex, the coefficients of the inverse transformation function are determined and brought into line with the sample thickness and the gap between the ECT and the control object, the ECT is balanced in the absence of the control object, and the ECT signal is analyzed in the presence of zero gap between the transducer and the test object. After adjustment has been completed, the ECT is located above the sample in a special positioning system allowing to move the transducer at a constant speed and display the measurement results in the form of a graph linked to the points of the sample welded seam. The transducer position coordinate was changed discretely, in increments of 5 mm, and measured as the distance from the edge of the sample to the point of the current sensor position.

3. Results and discussion
The value of the voltage inserted in the transducer measuring winding, which carried information about various defects in the control object, was accepted as the controlled parameter.

Figure 5 shows the change in the added voltage when moving the transducer along sample No. 1. The graphs are shown for registering the voltage at a frequency of both the current supplied to the exciting winding and equal to 500 Hz, and at a current frequency of 3000 Hz. Normalization of the
change in the added voltage within the scope of action of the edge effect is made according to the voltage measured in the center of defect-free sample No. 4.

![Figure 5](image)

**Figure 5.** Change in the added voltage when moving the transducer along sample No. 1.

From the graph, it follows that there is a significant drop in the measuring winding inserted voltage in the region of defect 1, the depth of which did not exceed 0.5 mm. The decrease in voltage occurs according to a law close to exponential. Such a dependence is observed when analyzing the graphs plotted during measurements both at 500 Hz and 3000 Hz frequencies.

However, in the region of defect 2 occurring at a depth of 1.5 mm, the picture of the decrease in voltage changes when passing over the defect. The voltage change during operation of the transducer at a frequency of 500 Hz still follows the exponential law, however, an analysis of the graph obtained during scanning at a frequency of 3000 Hz shows a significantly smaller drop in the applied voltage, which occurs according to a law close to linear. This is due to the defect increased depth, at which scanning at high frequencies does not provide obtaining of high-quality results.

Figure 6 shows the change in the applied voltage when moving the transducer along specimen No. 2 containing a defect representing a corrosion pin-hole weld defect model. A sharp transducer signal dropout is clearly visible, that is much shorter compared to the dropouts in the area of Sample No. 1 and is clearly noticeable at any current frequency of the eddy-current transducer generating winding.

![Figure 6](image)

**Figure 6.** Applied voltage when moving the transducer along specimen No. 2 containing a defect representing a corrosion pin-hole weld defect model.
Figure 7 shows the change in the applied voltage when studying Sample No. 4 with a defect represented by a model faulty fusion with different weld filling degrees (30%, 60%, 90%).

![Figure 7](image1.png)

**Figure 7.** Applied voltage when studying Sample No. 4 with a defect represented by a model faulty fusion with different weld filling degrees.

It can be seen that the defect with 30% filling of the weld is the most noticeable when scanning at all frequencies. As can be seen from the graphs, the voltage drop occurs exponentially at both frequencies. The defect with a 60% degree of filling is difficult to scan at high frequencies, which is apparently due to the deep occurrence of the defect and the weld material distribution in its upper part.

When scanning the defect with a 90% degree of filling, it is practically indistinguishable from a defect-free weld the voltage change graph for which is shown in figure 8.

![Figure 8](image2.png)

**Figure 8.** Applied voltage when studying Sample No. 4 with a defect represented by a model faulty fusion with different weld filling degrees.

4. Conclusions
As the studies have shown, the eddy-current method can be effectively used for quality control of welded seams in steel alloys used in transformer oil tanks. High sensitivity was observed to pin-hole
defects of corrosion type, weld faulty fusions and cracks. Various frequency-dependent signal informativity has been established over defects occurring at different depths. Frequency change during scanning and a corresponding signal amplitude change allows to make a conclusion about the type and depth of the defect.

References
[1] Sundaram B A and Kesavan K S 2018 J. The Institution of Engineers: Series A 90 729
[2] Konnov V 2013 Contr. Diagn. 3 68
[3] Rifai D, Abdalla A, Razali R and Ali K 2017 Sensors (Basel). 17 (3) 579
[4] Park G S and Park E S 2002 IEEE Trans. Magn.. 38 (2) 1277
[5] Kumar R and Rao Ch 2007 (Proc. Int. Conf. Materials for Advanced Technologies vol 1, (Singapore)
[6] Gruger H 2007 Sens. Actuat. 106 326
[7] Yashan A, Becker R and Klein A 2002 Proc. 8th European Conf. NonDestructive Testing vol 1 (Spain, Barselona)
[8] Sharatchandra W S 2011 Insight 53 (7) 377
[9] Al-Qadeeb F E 2005 Proc. 3rd MENDT –Middle East Nondestructive Testing Conf. Exhibition vol 1 (Bahrain, Manama)
[10] Zhang J and Liu X 2019 Sens. and Act., A: Phys. 288 10
[11] Dmitriev S F, Malikov V N and Ishkov A V 2017 Mater. Sci. Forum 906 147
[12] Dmitriev S, Malikov V and Sagalakov A 2016 AIP Conf. Proc. 1785 626-9