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Research on the welded seams of aluminum alloys using super-miniature eddy current transducers

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Abstract. Based on the eddy current transducer of the transformer type, a measuring system has been developed that makes it possible to investigate the welded joints obtained by friction stir welding (FSW). The main technical information about the eddy current converter being used is given, and a measurement procedure is described that allows to search for defects in welded seams of aluminum plates. The device allows to automatically change the main operating frequency of the device and the cutoff frequency of the filtration system. The experiments were carried out on aluminum-magnesium alloy plates being connected by friction welding. In the article, the results of measurements are presented, allowing to estimate the quality of a welded seam and to answer a question on reliability of welding.

1 Introduction

A wide distribution in modern technology was obtained by the structures made from alloys based on aluminum. The use of these alloys in such industries as aircraft building, automotive industry, and space engineering presents increased requirements to the structure and mechanical properties of the material. One way to create a design is welding, but for some aluminum-based alloys, melting welding is not always possible. To connect elements of these alloys, special methods and techniques must be used. One of the most effective way is the friction stir welding [1-5]. The produced welded joints, due to significant temperature and deformation gradients, are characterized by increased heterogeneity and structural defectiveness. With external mechanical action, defects in the structure of the welds cause premature cracking and fracture.

Due to the fact that the manufactured structures can be used in extreme operating conditions, this circumstance requires a thorough study of welded joints [6-7].

In the production of hull elements made of aluminum alloys is a widely used the method of friction stir welding (FSW) [8].

This method makes it possible to obtain all-in-one quality connections even from those alloys that do not yield to electric arc or argon-arc welding, which is especially important in the development and improvement of hull elements with increased strength and reduced dimensions and weight. In recent years, this type of welding is widely used by a number of

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large aircraft concerns, such as Boeing, Airbus, etc. In the Russian Federation, on an industrial scale, FSW is used, in particular, at the CJSC Cheboksary enterprise “Sespel” when manufacturing sealed containers for automobile semitrailers, intended also for the transport of dangerous goods. It should be noted that the welded joints obtained by this method have a specific set of defects different from the defects characteristic for fusion welding, which requires the development of a comprehensive technique for diagnosing the quality of the welds and improving the overall situation in industry [9-11, 22].

In the paper [12], a technique was developed to detect defects in the joint volume using ultrasound and X-ray inspection methods. For the ultrasonic method using a phased array antenna, it is shown that this method can detect defects throughout the weld seam with a high degree of reliability of the results being obtained.

But, in addition to the defects present in the seam volume, surface defects, such as root penetration, pore,s and cracks in the surface layer, have a significant effect on the strength of the joint. One of the most effective and accurate methods for detecting defects located in the surface layer or in a thin near-surface layer is the eddy current control method.

A number of authors have conducted studies to find the most reliable methods for determining small defects in a weld seam obtained using friction stir welding.

Catalin Mandache and co-authors [13] used an ultrasonic method to investigate alloys being connected by FSW. This method allowed to detect defects of deep occurrence, but the accuracy of controlling for the surface defects was low.

A. Lamarre et al. [14] was one of the first to apply a matrix of several ultrasonic sensors to control the weld obtained using friction welding.

An effective method for studying the quality of aluminum alloys is non-destructive eddy current testing.

Neil Goldfine and co-authors [15] developed an eddy current sensor capable of detecting defects in a welded joint in aluminum obtained by the FSW method measuring more than 150 micrometers.

A. Lamarre and co-authors [14] used a matrix of ultrasonic and eddy current sensors, which made it possible to effectively study the welds obtained by the FSW method.

The difficulty of using the eddy current method to search for defects in the welded joint consists in changing the electrical conductivity during the friction welding process itself with mixing [16].

P. Johnston and co-workers [17] used the subtraction of signals from two eddy current converters and digital processing of the signal received from the measuring winding to obtain more accurate results. They were able to find defects, the sizes of which started from 60 micrometers.

Li and co-authors [18] used a number of methods for nondestructive testing on a welded aluminum alloy 2219-T6 with additions of copper, silicon, manganese, iron, etc. They managed to achieve a high scanning speed by combining different methods.

Hu et al. [19] also used magnetic field sensors to study the welded joints obtained by FSW. They established that the magnetic permeability of such a welded seam changes significantly, which made it possible to use the eddy current method to find model defects having a size of the order of 13-130 mm.

A new non-destructive testing system based on the eddy current method was introduced in [20]. This system consisted of an eddy current sensor and a system for generating, amplifying, and processing signals, as well as an automatic displacement system for an eddy current sensor. This system was developed to detect microscopic defects on aluminum alloys being connected by FSW methods. The experiments were carried out on AA2024 alloys and showed that this system allowed detecting defects with dimensions from 50 micrometers.

Thus, the task of developing an eddy current converter capable of investigating welds obtained by the friction stir welding method and the creation of an eddy current measuring system capable of detecting defects in such materials is of particular relevance.

The purpose of this work is to identify defects in the welded FSW compounds of aluminum alloys using an eddy current transducer, as well as to develop a procedure for eddy current testing of these compounds.

2 Methods and approaches

The ultra-miniature VTP is designed for local control of the physical parameters of aluminum alloy plates [23-24]. The parameter to be determined is the electrical conductivity of the material and its distribution over the surface, as well as the object's thickness. The method of eddy currents is based on the dependence of the intensity and distribution of eddy currents in the monitoring object on its geometric, electromagnetic (and related) parameters, as well as the mutual position of the measuring transducer and the monitoring object.

The eddy current transducer is connected to the sound card of a personal computer with special software developed in C++ language under the Windows operating system. The software controls the supply of voltage to the exciter winding of the VTP and reads the voltage values (in conventional units) from the measuring winding, taking into account the preliminary calibration, and transfers the obtained data to the values of electrical conductivity.

Cores were used in our study in the form of a pointed pyramid. The cores were made of ferrite 2000 Nm3 with a magnetic permeability of 500. On their basis, VTPs with exciting, measuring, and compensating windings were designed. The compensation winding connected to the measuring winding is designed to subtract the signal of the exciting winding from the resulting signal. The exciting and measuring windings contain 200 turns, compensating winding – 160-180 turns. For winding, the copper wire of 5 microns is used. The diameters of the measuring and exciting VTP windings are 0.05 and 0.3 mm, respectively.

The eddy current transducer represents a transformer with a measuring, exciting, compensating winding and a magnetic core located inside a cylindrical platform. On the outer side of the platform, tracks are cut for windings impregnated with a compound at a temperature of 200°C in order to prevent destruction when a ferrite screen is placed to locate the electromagnetic field at the monitoring site. Outside, the VTP is encased in a corundum washer, which protects the core from contact with the object of control.

The characteristics of the developed VTP can effectively localize the magnetic field within the area of 2500 μm2 and provide a significant depth of its penetration into the object under investigation when operating at sufficiently low frequencies [22].

The developed measuring system works as follows. The personal computer controls the generator of rectangular voltage pulses with a repetition frequency f and amplitude U. In accordance with the measuring task, the repetition frequency and the amplitude of the pulses are set. To convert the signal into a sinusoidal form, the generated voltage pulses are applied to two integrators being connected in series. After conversion, the signal power is increased in the power amplification block (the gain is 20±2). The amplified signal is applied to the exciting windings of the inductance of a VTP. The sinusoidal current acting in the VTP coils creates an electromagnetic field that excites eddy currents in the electrically conductive object. The electromagnetic field of eddy currents affects the measuring windings of a VTP, inducing an electromotive force (EF) in them, which carries information about the structural inhomogeneities of the monitoring object in the zone of action of the VTP. The EF is amplified in a special selective amplifier, based on a two-stage modified Delnan filter with multi-loop feedback. The classical filter circuit was supplemented with a second stage of selective amplification, designed to increase the amplitude of the signal at a given frequency. As a result of connection of the second stage, the filtration system has a high stability and low sensitivity to a small spread in the parameters of the circuit elements.

Elements of the filter are designed to work at a frequency of 300-700 Hz. After filtering, the signal goes to the amplitude detector and then to the personal computer via the analog-to-digital converter. Due to the simultaneous control of the frequency of the generated signal on the exciting winding and the cutoff frequency of the filtration system, a useful signal is generated that carries information about the distribution of electrical conductivity within the object, in particular, about possible defects in the object. The program control allows changing the working frequency of the measuring system.

Defectoscopy of aluminum alloys, connected by means of FSW, was carried out with the help of VTP, the field strength of the exciting winding was 800 a/m. The measured characteristic is the introduced voltage induced by the field of eddy currents arising in the monitoring object. Before the measurement was started, the sensor was calibrated, which consisted in determining the insertion voltage from the area free from defects. Calibration was performed at a frequency of 100-1000 Hz. After that, the sensor moved over the scanned defective area with the registration of the voltage converter being inserted into the measuring winding. In this case, the frequency was varied in the range 100-1000 Hz in steps of 100 Hz. The frequency was determined, which ensures the greatest deviation of the applied voltage from the value of the voltage being obtained in the defect-free region of the sample. The voltage value corresponding to this frequency was considered as a parameter, according to the behavior of which the presence of a defect was judged. The scanning itself was carried out by moving the sensor across the weld or across the defect area.

The diameter of the measuring winding of the sensor used for scanning was 0.05 mm, the size of the scanning area on the surface of the sample was 0.1 mm, the time of one measurement at one frequency was 0.1 seconds, all frequencies were sampled 1 second, the calibration time was 0.5 seconds.

3 Results and discussion

Sample No. 1: two plates of aluminum-magnesium alloy bein connected by friction welding (Fig. 1a). The thickness of the plates was 8.3 mm. The width of the weld was 2 cm. The scanning was carried out by moving the sensor perpendicularly to the seam line, measuring the distance from the calibration area to the measurement area.

a) б)

Fig. 1. A photograph of the surface of samples No. 1 (a) and sample No. 2 with marked scanning zones (b).

In experiments with the sample No. 1, it was found that plates welded together gave different values of the applied stress, which obviously indicated different materials of the plates. The results of the experiment are shown in Fig. 2. The boundaries of the weld seam correspond to the drop in the applied voltage.

At the edges of the welded seam, it is possible to see sections of a significant drop in the applied stress, corresponding to the boundaries of the weld.

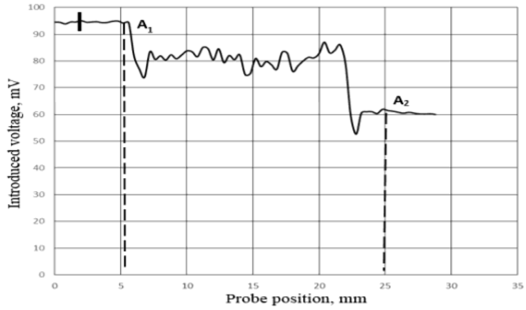


Fig. 2. The value of the applied voltage on the measuring winding of the transducer in the weld region. A_1-A_2: the boundaries of the welded seam; l: the transducer's position, U: the voltage applied to the measuring winding of the converter.

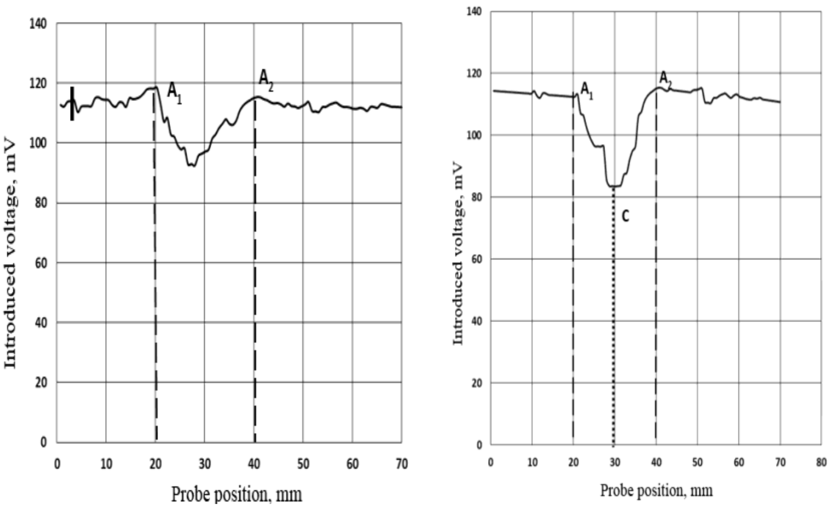
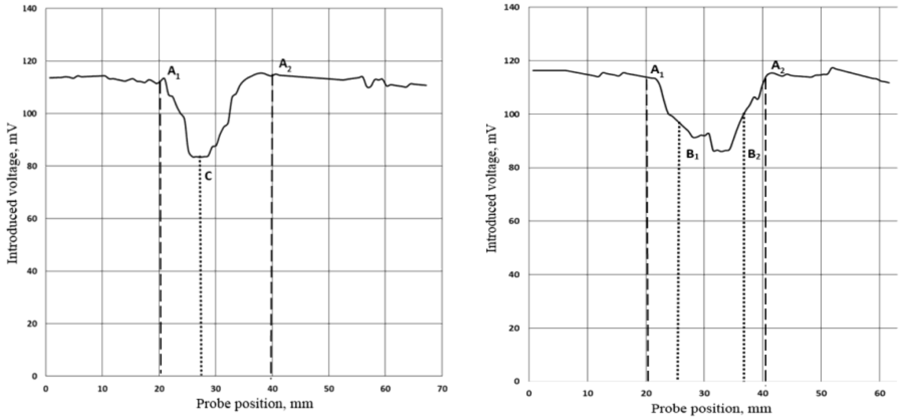


Fig. 3. Measurement results for welded seams with defects, Zone 1 (a), Zone 2 (b). A_1-A_2: the weld boundary; C: the crack location.

The plate is 5 mm thick with technological defects in the weld region (the scanning areas are indicated by the numbers 1, 2, 3, 4, 5, 6, 7, 8, which is shown in Figure 1b.) Scanning was carried out by moving the sensor perpendicularly to the seam line, with measuring the distance from the calibration area to the measurement area. In this sample, the scanning was performed by moving the sensor over the weld region with the defects contained therein. In region 1, inside the sample, a cavity was located with the diameter of 2 mm; the depth of occurrence from the scanning surface was 3 mm. The cavity was fixed during scanning with the use of an eddy current transducer operating at a frequency of 700 Hz (Figure 3a). The boundaries of the weld seam correspond to the drop in the applied voltage. The dotted area indicates the defect area. The voltage drop across the measuring winding of the transducer in the defect area was 25 mV if compared to the calibration region and 7 mV if compared to the weld region.

In areas 2 and 3, there was a surface crack on the weld seam. The width of the crack is 0.2 mm. The surface crack was easily fixed by the converter at almost all frequencies: the change in the applied voltage was about 35 mV if compared to the calibration region and about 15 mV in comparison with the weld region (Fig. 3b, 4a).

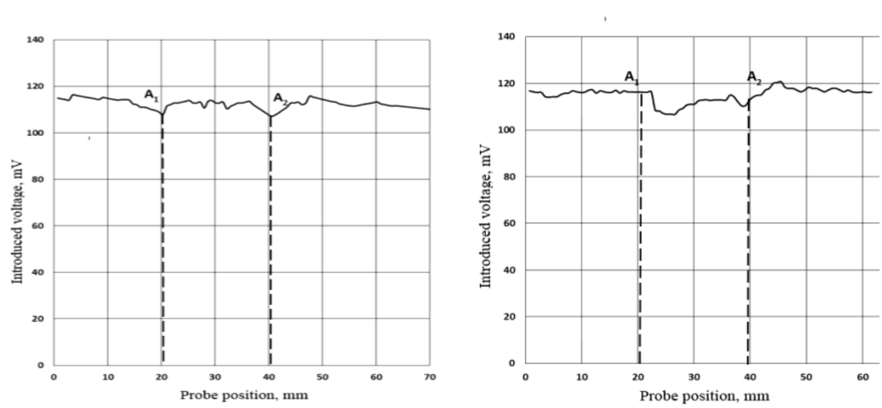


a b

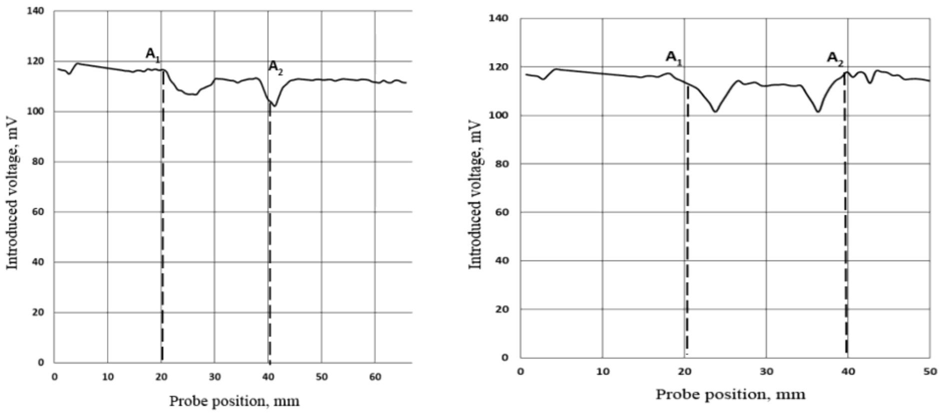
Fig. 4. Measurement results for the welded seams with defects, Zone 3 (a), Zone 4 (b). A_1-A_2: the weld boundary; C: the crack location; B1-B2: the cavity boundary.

Zone 4 is a profiled internal cylindrical cavity located on the underside of the plate, 4 mm in depth, 1.5 mm in diameter, with a depth of 1 mm from the scanning surface, which was clearly visible on the transducer (Fig. 4b.). The change in the insertion voltage in the region of the cavity was 30 mV if compared with the calibration region and 10 mV in comparison with the weld region.

Zones 5-8 were a weld region having internal cavities (holes) marked with characteristic dips at the edges of the seam. (Figure 5a-d). The drop in the insertion voltage at the gaps was 5-10 mV if compared to the neighboring defect-free region of the sample. Since a similar pattern is observed in sample No. 1 (Fig. 2), it can be concluded that this feature is inherent in this type of welding.



a b



c d

Fig. 6. Measurement results for the welded seams with defects, Zones 5-8 (a-d). A_1-A_2: the boundaries of the welded seam.

4 Conclusion

A measuring system designed for the study of plates made of aluminum-magnesium alloys, connected using the friction stir welding method, has been developed. The conducted research demonstrates the possibilities of the eddy current method for controlling the search for ultra-small defects in these welds. Ultra-miniature VTSs, designed on the basis of the pyramidal-shaped cores, can effectively detect cracks and cavities having the diameter of 0.2 to 2 mm, lying at the depth of 3 mm. Also, it shows the ability to control the weld's edges.

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