Investigation of welded joints of aluminium alloys using subminiature eddy-current transducers

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Abstract. The authors developed a measuring system based on subminiaturized eddy-current transducers aimed at examining locally the defects of welded joints in aluminium-magnesium alloy plates connected by means of friction stir welding. The authors made a modification of the Delyann filter, which allowed them to increase considerably the signal-noise relations. The dependency of the eddy-current transducer response on defects was provided, i.e. concealed cuts and openings inside the welded joint, at the frequencies of 100-10000 Hz of the exciting winding.

1. Introduction
Constructions made of aluminium alloys are frequently applied in current technology. Application of these alloys in such spheres as aircraft engineering, automobile construction, spacecraft engineering, demands higher standards of the structure and mechanical characteristics of the material. One of the ways to connect elements into a construction is welding. However, common types of fusion welding are not always applicable for some aluminium-based alloys. In order to join elements of such alloys, one has to use special methods and processing technologies, among which, friction stir welding is one of the most efficient [1-4].

Due to significant temperature and deformity gradients, obtained welded joints are characterized by high inhomogeneity and deficiency of the structure. Affected by external mechanical impact, structural defects of the welded joints cause early crack formation and destruction. As soon as the obtained constructions can be used in extreme operation conditions, the mentioned circumstance requires the performance of welded joints thorough diagnosis [5]. Currently, friction stir welding (FSW) is widely applied in the production of body frame elements made of aluminium alloys [6]. This method allows us to get permanent qualitative joints even made of those alloys that are not subject to electric-arc welding or argon-arc welding. It is especially important for designing and refining body frame elements, which have increased strength and reduced size and mass. In the recent years, such type of welding has been widely applied by a number of large aero corporations, such as «Boeing», «Airbus» and others. In the Russian Federation, ZAO Cheboksar enterprise “Sespel”, for one, uses FSW on an industrial scale producing insulated vessels for semi-trailers intended i.a. for the transportation of dangerous goods. One should also note that welded joints obtained with the help of this method are characterized by a specific set of flaws different from the ones that are characteristic of fusion welding which requires the development of a complex procedure for the diagnosis of obtained joints quality [7-
In work [9], the methodology of detecting flaws in the joint volume was developed with ultrasonic and X-ray technique application. The ultrasonic technique with the use of phased array antennas demonstrates capability of detecting defects within the whole volume of the weld pass. The obtained results are highly valid.

However, except for defects, located within the joint volume, surface defects, such as bridging, interstices and cracks in the surface layer and others, influence the joint strength substantially. One of the most highly-efficient and exact methods, which allows detecting defects located in the surface or in the thin subsurface layer, is the eddy-current control method.

Some authors have performed research to discover reliable NDT methods that allow one to detect micro-defects in alloys bonded by friction stir welding (FSW). Nevertheless, in conductivity materials, when high reliability is required as mentioned before, eddy current is the most adequate technique. However, eddy current (EC) flow can change not only due to defects, but also due to the variations of the probe lift-off. The high-sensitive lift-off effect of conventional EC probes introduces noises which mask the signal of small defects, making their detection difficult or even impossible. Moreover, the low sensitivity of common EC probes as well as other electronic issues may not enable to distinguish between defect and non defective conditions.

Catalin Mandache et al. [10] applied PEC in FSW, but even in the presence of significant size root defects, the inspection accuracy is low. PEC variant has the capability to detect deeper defects, nevertheless micro-defects in FSW can hardly be detected. Neil Goldfine et al. [11] have developed a MWM® detector, which is able to discover some FSW defects, but applicable only to large ones (as a rule, above 150 micron). Lamarre et al. [12] were among the first to apply phased array ultrasonic on FSW, and P. H. Johnston [13] highlighted difficulties in detecting the oxides alignment defects on the nugget of the FSW using this NDT technique.

M. Moles et al [14] used ultrasonic and eddy currents arrays for inspection of friction stir welds in aluminum. L. S. Rosado et al [15] used eddy current probe to detect the imperfections in the friction stir welding of metals. Lie et al [16] have reported on multiple nondestructive testing methods on the FSW of AA 2219-T6. Hu et al [17] also employed a high-precision magnetic sensor to detect the weld defects in aluminium Friction stir welds.

In [18], a new NDT system is presented. The system is composed by a planar eddy currents probe (IONic probe), electronic devices for signal generation, conditioning and conversion, automated mechanized scanning and analysis software. The IONic system was developed mostly to be used for the micro-defects detection on aluminum solid state processed alloys by FSW. The experimental results in AA2024 welded by FSW clearly show that this system is able to detect imperfections around 50 µm, which contribute to an increase the reliability on NDT of micro imperfections.

Therefore, the task of developing an eddy-current transducer capable of examining welded joints obtained by means of friction stir welding and the creation of the eddy-current measuring system capable of detecting flaws in such materials seems to be crucial.

The purpose of this work is the detection of defects in welded FSW joints of aluminium alloys with the application of the eddy-current transducer and the development of the eddy-current control procedure for such joints.

2. Materials and methods
The authors have developed a subminiature eddy-current transformer for local monitoring of the physical parameters in titanium-alloy plates and weld seams [19]. In contrast to existing sensors, it permits local measurements with sections measuring a few microns to depths of the order of 5 mm. The electrical conductivity of the alloy is directly measurable, and its distribution over the sample surface and thickness may be readily established. The eddy-current method is based on the dependence of the current magnitude and distribution on the geometric and electromagnetic parameters of the sample and on the mutual position of the sensor and the sample. Basic informative parameter \( \beta_0 \) is a generalized characteristic of the object, the eddy-current sensor, and the frequency of
The electromagnetic field [20]. One needs to develop an adequate model of the response of a eddy-current transformers of plate type, which are sensitive to many variables and permit reproduction of the voltage hodograph at small values of $\beta_0$. The authors have plotted hodographs illustrating the influence of various parameters on the induced voltage on the basis of the proposed model [20]. The eddy-current transformer is connected to the sound board of a computer with special software that controls the voltage in the transformers exciting winding and also reads the voltage at the measuring winding (in arbitrary units). On the basis of preliminary calibration, these readings are converted to values of the electrical conductivity. The exciting winding (diameter $D_1 = 0.12$–0.13 mm) of the superminiature eddy-current transformer consists of ten turns of copper wire (cross-sectional area is 5 µm$^2$). The measuring winding (diameter is 0.05–0.08 mm) consists of 130 turns of copper wire (cross-sectional area is 20 µm$^2$). To minimize the influence of the exciting winding on the final signal, the circuit includes a compensation winding that consists of 20 turns of copper wire (cross-sectional area is 5 µm$^2$), connected to the measuring winding in such way that the voltage of the exciting winding is subtracted from the result. The windings are wrapped around a core of 2000 NMZ ferrite (relative magnetic permeability is $\mu_{\text{max}} = 500$ or else of 81NMA alloy annealed by a special method (if greater localization of the magnetic field is required)). The core consists of a tetrahedral pyramid (height is 1 mm), with a square base (sides are 0.2 mm). The measuring winding rests on the points of the pyramid, which improves the localization of the magnetic field.

The eddy-current transducer (Figure 1) is a transformer with measuring (1), exciting (2), and compensation (3) windings and magnetic circuit 4, which is located inside cylindrical platform 5 with tracks that are cut on the external side for windings. The platform is impregnated with compound 6 at a temperature of 200°C to prevent the disintegration of the windings when ferrite screen 7, which is intended for the localization of the electromagnetic field on the tested object, is put in place. From the outside, the transducer is contained in corundum washer 8, which protects core 4 from contacting the tested object.

![Figure 1. A block diagram of the eddy-current transducer.](image)

Such transformers permit effective localization of the magnetic field, so that defects as small as 250 µm may be detected. In addition, the magnetic field penetrates into the sample to a considerable depth when working at relatively low frequencies. The corresponding software is written in language C++ for the Windows operating system. By means of the Windows mixer subsystem, the software controls the voltage applied to the exciting winding, thereby specifying the amplitude and frequency of the sinusoidal digital signal from the virtual generator.

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 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 voltage $U_m$ 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.
3. Scanning welded joints of aluminum alloys

Flaw detection was conducted with the help of a transformer eddy-current transducer of the attachable type, the field density of the exciting winding being 800 A/m. The measured characteristic is the input voltage induced by the eddy-current field in the monitored object. The sensor calibration was performed before the beginning of the measuring operations, the calibration itself consisting in the definition of the input voltage from the defect-free section. The calibration was performed at the frequency of 10000 Hz. After that, the detector was moving over the scanned defective area, while the voltage input in the measuring winding of the transducer was being registered. At the same time, the variation of the frequency in a 100 – 1000 Hz range at a pitch of 100 Hz was performed. The authors tried to determine the frequency that provided for the most input voltage deviation from the voltage value obtained at the defect-free section of the specimen. The voltage value corresponding to this frequency was viewed as a parameter, which behavior allowed inferring the presence of a defect. The scanning itself was conducted by means of the sensor moving crosswise the weld seam or of the defective section.

The diameter of the measuring winding of the sensor used for scanning was 0.5 mm; the length of the scanned section on the surface of the specimen was 0.1 mm; the duration of one frequency measuring amounted 0.1 sec, for all frequencies – 1 minute; the calibration time was 0.5 sec. Specimen №1 (Figure 2.a.) represents two plates made of aluminium-magnesium alloy joint by means of friction stir welding. The thickness of the plates was 8.3 mm; the breadth of the weld seam equaled to 2 cm. Scanning was performed by means of the sensor moving perpendicular to the seam line with measuring the distance from the calibration section to the measured section.

![Figure 2](image)

**Figure 2.** Photo of Specimen №1 and Specimen №2 surface with marked scanned areas.

The experiments with Specimen №1 allowed us to state that the plates joint with a weld seam provide different values of the input voltage, which obviously indicates difference in the materials of the plates. The results of the experiment are presented in Figure 3. The decline of the input voltage corresponds to the welding edges. Along the edges of the welded joint, one can observe the areas with significant decline of the input voltage corresponding to the welding edges.

![Figure 3](image)

**Figure 3.** Amount of the voltage input to measuring winding of the transducer in the area of a weld seam. Scanning frequency is 700 Hz. A₁-A₂ are welding edges.

Specimen №2 (Figure 2.b.) is a 5-mm-thick plate having technological flaws in the area of the welded joint (scanned sections are labelled with numbers 1, 2, 3, 4, 5, 6, 7, 8 and are presented in the picture). Scanning was performed by means of the sensor moving perpendicular to the seam line with
measuring the distance from the calibration section to the measured section. In this specimen, scanning was performed by means of the sensor moving above the weld seam area having the flaws enclosed. In Area 1, inside the specimen, there was a cavity having the diameter of 2 mm, its depth of location from the scanned surface equaled 3 mm. It became possible to establish the cavity while scanning with the help of the eddy-current transducer working at the frequency of 700Hz (Figure 4.a.). The decline of the input voltage corresponds to welding edges. The dotted line defines the flaw area. The voltage decrease in the measuring winding of the transducer in the flaw area equaled 25 mV in comparison with the calibration area and 7mV compared to the welded joint area.

Figure 4. Measurement results for the defective weld seam, Area 1 (a), Area 2 (b). $A_1$-$A_2$ are welding edges, C is the location of the crack

Areas 2 and 3 hosted a surface crack on the welded joint. The breadth of the crack is 0.2 mm. The surface crack was easy to detect by the transducer at about all the frequencies. The change of the input voltage equaled 35 mV compared to the calibration area, and approximately 15 mV - in comparison with the weld seam area (Figure 4.b., 5.a.).

Figure 5. Measurement results for the defective weld seam, Area 3 (a), Area 4 (b). $A_1$-$A_2$ are welding edges, C is the location of the crack, $B_1$-$B_2$ are the cavity edges.

Area 4 is a milled inside cylindrical cavity located on the reverse side of the plate. Its depth is 4 mm, while its diameter is 15 mm and the depth of location from the scanned surface equaled to 1 mm, the cavity being rather easy to detect with the help of the transducer (Figure 5.b.). The change of the input voltage in the cavity area equaled 30 mV compared to the calibration area and 10 mV compared to the weld seam area.

Areas 5-8 were the welded joint area having internal cavities (openings) marked by distinctive dips along the edges of the seam (Figure 6.a-d.). The input voltage decrease in the dips equaled 5-10 mV in comparison with the neighboring flawless section of the specimen. As soon as the same phenomenon
was observed in Specimen №1 (Figure 3), one can make a conclusion that this peculiarity is characteristic of the type of welding under consideration.

\[ a \quad b \quad c \quad d \]

**Figure 6.** Measurement results for the defective weld seam, Areas 5-8 (a-d). $A_1$-$A_2$ are welding edges

4. Conclusion

The authors worked out a measuring system aimed at the examination of plates made of aluminium-magnesium alloys joint by applying the friction stir welding method. The conducted research demonstrates the potential of the eddy-current control method applied to search for midget flaws in the welded joints. Subminiaturized eddy-current transducers, constructed on the basis of pyramid-shaped cores, allow effectively detecting cracks and cavities having the diameter from 0.2 to 2 mm located at the depth of up to 3 mm. In addition, the authors demonstrated the possibility to control the areas of weld seam edges.

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