Measuring system for studying quality of welded joints of titanium plates by using subminiature eddy current transducers

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Abstract. This article contains the main technical information on the eddy-current transducer (ECT) used. This article describes the measurement procedure to control welds of titanium alloys, including the use of two superminiature ECT, one of which is to be fixed above the weld, and another is to be used directly for scanning. The experimental results obtained by means of the developed measuring system for samples of various titanium plates joined by welds are presented. Likewise, a poor-quality weld can also be detected by a dramatic drop in amplitude of the signal when scanning the weld/welded material. The article presents the results of studies of titanium samples joined by a faulty weld, samples joined by a completely faulty weld, and also samples joined by a defect-free weld. The obtained dependences make it possible to determine the quality of the weld by the signal of an eddy-current transducer and to draw a conclusion about the reliability of welding.

1. Introduction
Titanium and its alloys occupy an important place among metal constructional materials due to their especially valuable physical and chemical properties [1] which include small specific gravity and big strength in normal and raised temperatures. Therefore, due to their properties, titanium and its alloys find multiple applications in construction of installations, pipelines, and chemical equipment [2–3], as, for example, a reactor made of an explosively clad steel titanium sheet [4, 5] or a welded technical titanium pipeline.

Military shipbuilding has begun to use titanium alloys for seagoing vessels and submarines [6]. The plate thicknesses used here are in the double digit millimeter range. Joining these thicknesses is a major challenge to the welding technique used.

Thereby, the increasingly higher use of titanium components to develop critical roles in the industry where high criteria of safety must be guaranteed requires an accurate NDT method. Penetrant testing (PT) methods are integrated as an NDT tool to locate surface flaws in non-porous materials from the manufacture up to the maintenance phase [7]. A hybrid PT method based on bacteria cells was successfully implemented as a NDT tool to inspect micro surface defects up to 700 µm diameter, in laser welds performed in titanium [8]. However its effectiveness is drastically affected by the surface conditions, requiring a complex procedure to avoid a false negative result [9]. On the other hand, digital radiography methods achieve a detection level of flaws with openings above 100 µm width in laser welded titanium specimens [10].
Under a non-complex sample preparation, eddy current testing is high impact technology to detect hidden (low frequency regime) or surface defects (high frequency regime) in conductive materials upon the application of a time-dependent magnetic field [11]. The presence of a discontinuity acts as a resistive barrier that perturbs the eddy current flow changing the magnetic field generated by it. Furthermore, the resistive losses also promote a thermal distribution along the surface which can be captured by combining thermographic NDT techniques with ECT. In [12] defects with a length of 780 μm are the threshold value for eddy current induced thermography employed for fatigue cracks in titanium. From a sensing point of view, inductive coil sensors are a widespread ECT probe [13], however their poor spatial resolution and limited sensitivity at low frequency compromises the detection of deeply embedded flaws and subtle topographic variations. Superconducting quantum interference devices (SQUIDs) have the potential to surpass the inductive coil sensors by detecting deep buried defects [14], however their high field sensitivity compromises the spatial resolution and requires an apparatus which operates at cryogenic temperatures. Therefore, ECT tools based on magnetoresistive sensors offer advantages over inductive coil sensors and SQUIDs due to an enhanced spatial resolution, high sensitivity, large bandwidth and an operating point at room temperature [15], being very promising candidates for an universal integration in NDT tools [16-18] to overcome the specifications imposed by the industry and achieve a detection range of micrometric surface flaws on low conductive titanium alloys.

Despite a significant number of modern means and methods of nondestructive testing, portable material diagnostic methods are rather narrowly functional. Despite the possibility of finding defects, they are not designed to evaluate the degradation of the material, and they do not allow one to conclude the possible timing of its further use and the risk of breakdowns. This is due to the inability to scan simultaneously at different depths, to search ultra-small defects and to analyze scans in real time.

Thus, the creation of eddy-current hardware and software complex, that allows to solve the problem of determining the soundness of the welded joint of titanium alloys, is a very relevant task.

2. Materials and methods

Subminiature ECT [19, 20] is designed for experimentally local studies of titanium-alloy plates and weld seams. The eddy current probe was made in the form of a transformer with a core on which epoxy impregnated coils are placed to prevent mechanical damage.

To test different conductive materials, a developed transducer is used, which is connected to a personal computer via a sound card that is used as a generator and as a signal transducer. The signal thus is sent directly to the energizing winding.

The structure of the developed ECNDT system: overlay eddy current transducer (ECT), generator, digital oscilloscope, digital interface, and personal computer with original algorithmic software.

The software is able to control the quantity of a signal applied to the energizing winding and also allows to read the voltage values from the measuring winding, which, taking into account the calibration, are converted into conductivity values. Coils were made of copper wire. The thickness of the coil is 5 μm. The eddy current probe was connected to the computer via standard audio card connectors. An audio card operating under the control of a special virtual generator and receiver is used to generate a signal on the exciting coil of the probe and receive a signal from the measuring coil. The developed system provides a significant depth of penetration of the field into the prototype system up to values of ~ 5 mm (at frequencies of 500 Hz). With the help of the software it is possible to effectively control the signal, which is applied directly to the energizing winding. Also with this software it is possible to receive a signal directly from the measuring winding. The impressed voltage can be controlled using a special mixer built into the Windows. With the help of this mixer, the frequency and amplitude parameters of the generator sinusoidal signal are set. In turn, the sound card makes it possible to extend the signal bandwidth, which is applied directly to the energizing winding.

To scan welds on titanium alloys, the eddy-current transducer was presented by two sensors with energizing and measuring windings. These sensors had the same electromagnetic characteristics and when scanning the weld were placed at a distance equal to or less than the width of the weld. This
location of the sensors provided simultaneous consideration of signals corresponding both to the welded materials themselves and welds. The sensors were located at the control area in such a way as to excite the eddy currents at the boundaries:

- first welded material / weld,
- second welded material / weld,
- only in the area of the weld in a variety of combinations.

Due to the amplification and filtering system, it is possible to effectively control the signals coming to the exciting coil and prevent interference with the signal coming from the measuring coil.

3. Experimental results

Two plates (S-1 and S-2) were chosen for carrying out of experimental researches. They had the thickness of 5 mm, length 50 mm and width of 20 mm. The roughness of the working surface does not exceed 1.6 microns.

3.1. Example 1. Inspection of a weld of type VT1-0 / VT1-0

As the first sample for scanning, there were two pieces of titanium VT1-0 / VT1-0 connected by welding. Meanwhile, a 1600 Hz signal was sent to the exciting coil, and the amplitude of the generated signal was 1.5 V. S-1 is plates made of titanium and joined by welds. Weld width — 4-5 mm. Scanning was made both along and transverse to welds in various areas.

Experiment No. 1 with S-1 was carried out along the weld, two strong drops of the signal amplitude were recorded. This corresponded to the fault location (areas 1 and 3). The results of the experiment are shown in Figure 1. The value of the voltage was introduced to the measuring winding of the transducer in the weld area when scanning along the plate. A₁-A₂ — the boundaries of the first defect (area 1), B₁-B₂ — the boundaries of the second defect (area 3).

Experiment No. 2 with S-1 was carried out along the weld through areas 1 and 3 (defects) and area 2 in the middle of the weld and free of defects. Scanning of area 1 showed that the weld had basically no effect on the signal of the eddy-current transducer. However, the defect (A₁-A₂) was significantly observed due to a significant drop in the signal amplitude (Figure 2).
Figure 2. The plot of signal received from a transducer when scanning area 1 is transverse to the plate. A1-A2 — defect boundaries.

Figure 3. The plot of signal received from a transducer when scanning area 3 is transverse to the plate. A1-A2 — defect boundaries.

Figure 4. The plot of signal received from a transducer when scanning across the plate through area 2.

Figure 5. The plot of signal received from a transducer when scanning across the defect-free part of the sample.

When studying area 3, which also had a defect, it was not possible to define the weld boundaries. The amplitude drop in a faulty area was observed (section A1-A2) in Figure 4. While studying area 2, which had any defects, the boundaries of the weld were still not observed. Since there was no defect in the area, the signal amplitude drops were not recorded (Figure 4).

For comparison, the results of scanning of a sample area without a weld are presented. The results were almost identical (Figure 5).

3.2. Example 2. Inspection of a weld of type VT1-1 / VT1-1.
As the second sample for scanning, there were two pieces of titanium VT1-1 / VT1-1 connected by welding. Meanwhile, a 1600 Hz signal was sent to the exciting coil, and the amplitude of the generated
signal was 1.5 V. S-1 is plates made of titanium and joined by welds. Weld width — 4-5 mm. Scanning was made both along and transverse to welds in various areas.

Scanning of samples along the weld. To assess the uniformity of the weld, the samples were scanned along the surface of the weld. Significant fluctuations introduced into the measuring winding were not recorded (Figure 6). According to this experiment, the weld had a uniform texture. However, this study does not give information on the quality of the weld, since according to its results we can make a conclusion on the uniform distribution of defects in the weld, and the absence of any defective areas in it.

Investigation of plates transverse to the weld. To compare the quality of the weld area with the area of the welded plates, a scanning was made transverse to the weld in such a way as to take both the weld area and the plate area (Figures 7, 8).

A dramatic amplitude drop of the voltage introduced to the measuring winding of the transducer was observed in the scanning area corresponding to the boundaries of the weld. This drop was especially observed if compared with the signal level of corresponding areas of the plates under study.

Figure 6. The plot of signal received from a transducer when scanning along the weld.

Figure 7. The plot of signal received from a transducer.

Figure 8. The plot of signal received from a transducer when scanning across the defect-free part of the sample.
Based on this experiment, we can make a conclusion on the poor quality of the weld that joined titanium plates of S-2. The results of destructive testing confirmed the poor quality of the weld used in this sample. At the same time, the study of sample No. 1 did not reveal any significant fluctuations in the amplitude of the voltage introduced to the measuring winding in the weld area. High quality of the weld of sample No. 2 was confirmed by the results of destructive testing.

*Attaching of plates without welding.* An additional experiment to interpret the results involved the joining of two titanium plates without welding (Figure 9). The results of the experiment were similar to the results obtained by scanning plates with defective welds (Figure 7). Hence, we can determine the influence of poor-quality weld on the eddy current probe signal.

![Figure 9](image.png)

*Figure 9.* The plot of signal received from a transducer when scanning along the weld.

### 4. Conclusion

The experiment demonstrated the possibility of using the developed hardware and software complex to assess the state of the weld of titanium plates. A poor-quality weld seam is clearly visible by the signal amplitude drop 10 times compared to the signal from the plates themselves. On the contrary, high-quality weld does not allow to detect any signal deviations when using the amplitude scanning method.

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