Automatic testing of welds of resistive elements of switching equipment of the superconducting magnetic system of the thermonuclear reactor ITER

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Abstract

The design and basic algorithms of the automatic eddy current control system for welds of resistive elements are described in the article. The resistive elements are assembled and welded from 73 steel plates, as a result of which the size and shape of each resistive element varies significantly. To create the scanning trajectory, a laser profile sensor is used, mounted on a robot manipulator next to an eddy current probe. Original algorithms using a neural network processing laser profile sensor's signals allow you to create a smooth scanning trajectory, and the micro-displacement system works out short sharp deviations in the shape of the weld. The procedure of automatic adjustment of the robot manipulator and eddy current probe is described.

1. Introduction

Automatic non-destructive testing of objects whose shape is significantly influenced by a large number of random factors requires automatic creating of a scanning trajectory for each instance.

2. Description of the test object

In the design of the elements of the switching equipment for power supply and protection of the superconducting magnetic system of the ITER thermonuclear reactor, powerful resistive modules are used, the location of which is shown in the layout of the ITER switching equipment, Figure 1, (*a*). The appearance of the resistive module is shown in Figure 1, (*b*), it consists of 4 resistive elements (RE), shown in Figure 1, (*c*). RE consist of molded steel plates welded together. The appearance of the welds is shown in Figure 1, (*d*). The design of the weld is shown in Figure 1, (*e*). The material of the welded plates is ferromagnetic steel 08J. Weld technology - non-consumable electrode arc welding (TIG-welding). The thickness of the plates to be welded is 1 mm, the penetration depth specified by the regulatory documentation is 1... 1.5 mm. The number of welds on one side of the RE is 72 pcs., the welds are located on both sides of the RE.

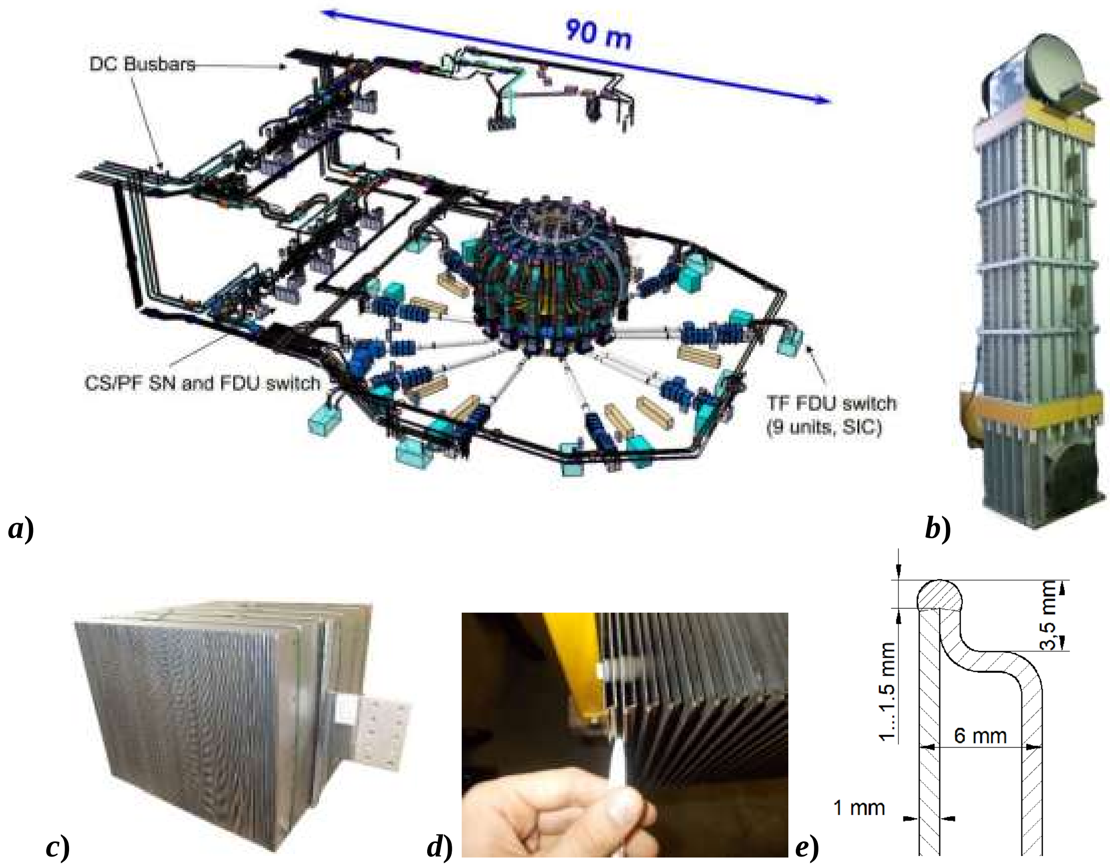


Figure 1. ***a*) layout of ITER switching equipment, *b*) resistor module PF, *c*) resistive element PF, *d*) welds of the resistive element PF, *e*) the design of the weld**

The welded plates are assembled manually on the assembly and welding equipment. The welds are located mainly in the same plane, but there are deviations in the location of some welds from the plane to several millimeters.

3. Description of the eddy current probe

The eddy current testing method with magnetization to saturation using an electromagnet is used to control the depth of penetration. The design of the eddy current probe (ECP), the magnetization and cooling system of the electromagnet is described in (1).

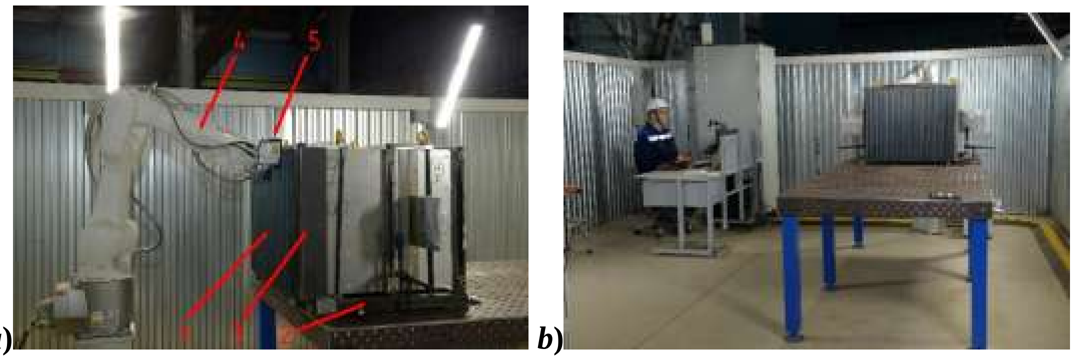
The appearance of the ECP installed on the robot manipulator is shown in Figure 2. The main components of the ECP are defined by numbers: 1 - a ceramic protective cap covering the coils of the ECP, 2 – rollers with which the ECP going along the weld,
3 – an electromagnet with branch pipe of the liquid cooling system, 4 – a box with an electronic board. In addition to the components of the ECP, in Figure 2, the number 5 defined a laser profile sensor.

Figure 2. Appearance of the eddy current probe

The ECP rollers going along the weld, perceive the force of attractivity of the electromagnet and provide a protective gap of 0.2 mm between the ECP and the weld.
For the correct operation of the ECP, the robot manipulator must provide normal conditions: the displacement of the ECP when setting on the weld with an accuracy of not less than ± 0.5 mm, the inclination of the ECP relative to the weld is not more than ± 0.3 °, rotation of the ECP around its axis relative to the weld no more than 0.2 °, scanning at a uniform speed of no more than 100 mm / sec, setting and removal of the ECP with the electromagnet disabled.

4. Description of testing conditions

Due to the large volume of testing, as well as due to the increased requirements for the accuracy of positioning the ECP on the weld during testing, a 6-axis robot manipulator KR 10 R1100-2, manufactured by KUKA, is used for scanning. The appearance of the site with the equipment is shown in Figure 3, (*a*, *b*). In Figure 3, (*a*), defined by numbers: 1 – RE, 2 – welding and assembly equipment, 3 - a reference test piece fixed to the welding and assembly equipment next to the RE welds, 4 – a robot manipulator, 5 – a ECP and a laser profile sensor fixed to the tool join point (TJP) of the robot manipulator.



a) ***b***)

Figure 3. The appearance of the equipment at the site

The RE in the assembly and welding equipment is installed on a sturdy table with the use of a bridge crane located in the workshop. Positioning of assembly and welding equipment is carried out manually with the use of deadlocks, which are dismantled before testing. Deviations when installing assembly and welding equipment on the table, due to the peculiarities of the rigging equipment, can reach 10 mm.

In addition to the above deviations, after welding the molded steel plates that made the RE, there is a distortion of the shape of the welds themselves. Plates with welded seam tend to bend in an arc.
Due to the imperfection of the welding technology, there are surges on the surface of the welds, with a height of 0.2 to 0.8 mm, Figure 4. These surges distort the required trajectory of the ECP. In addition, the size of some surges exceed the size of the protective gap of the ECP and begin to wipe the protective ceramic cap of the ECP, which consumes its resource.

a)  *b*) 

Figure 4. *a*) Surges on welds, *b*) close-up surges

5. Scanning trajectory create system

To ensure the required accuracy of the positioning of the ECP, the scanning trajectory cannot be universal and must be create individually for each RE. A 2D laser profile sensor 2900-50 manufactured by Microepsilon is used to create the scanning trajectory. The laser profile sensor is placed on the TJP of the manipulator next to the ECP.
In order to create the trajectory of the ECP scanning, a scan of the intended area of the welds is carried out with a laser profile sensor. In one pass, the laser profile sensor scans 4 welds, the scanning trajectory of the laser profile sensor is set fixed for a given design of the RE. The trajectory of scanning with a laser profile sensor is shown in Figure 5.

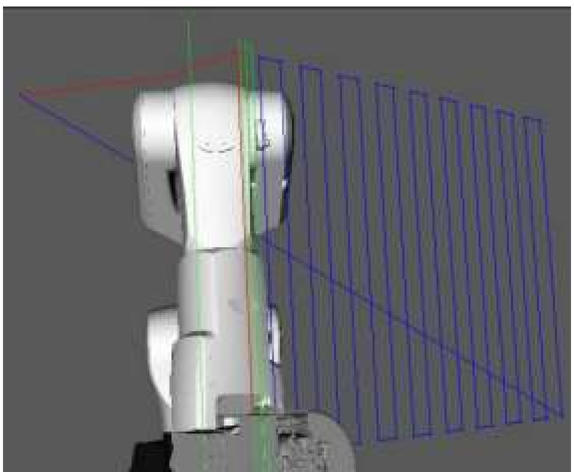


Figure 5. The trajectory of scanning a resistive element with a laser profile sensor

When scanning weld, data describing the shape of the profile of the welds at each point of the trajectory is received from the laser profile sensor. An example of the source data is shown in Figure 6 with bold lines. The data is filtered by the screening method according to the threshold of the mean square deviation, the value of which is selected experimentally for the combination of the selected type of laser profile sensor and the reflectivity of the test object. The weld seam has a complex shape, close to semicircular. The custom T-1200 convolutional neural network CNN, specialized for this application, is used to determine the parameters of the seam. It is characterized by invariance and high efficiency of object recognition. In the profile of the weld, seams are found, the shape of which is interpolated by a semicircle 1.
The radius of the detected semicircles and the coordinates of the location of their centers relative to the coordinate system of the robot manipulator 2 are determined. Through the last points of the sample 3, the plane of the location of the welds 4 is create, relative to which the plane 5 shifted towards the location of the robot manipulator is create. Normals to the semicircles 6 detected by the neural network are create from this plane. The coordinates of the peak of the weld 7 are determined as the intersection point of the normal and the semicircle.

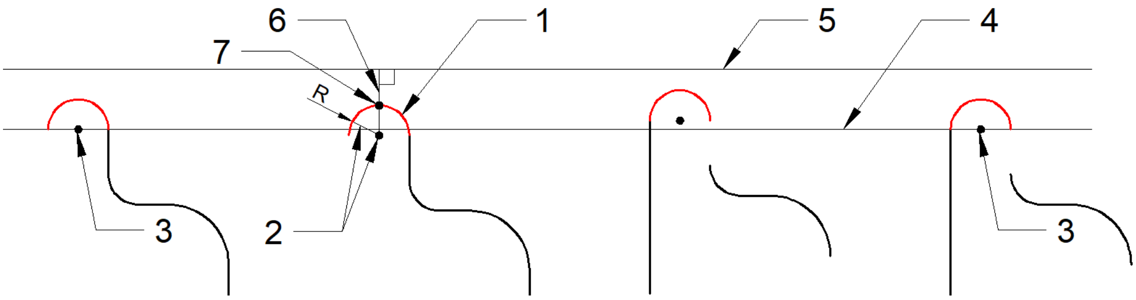
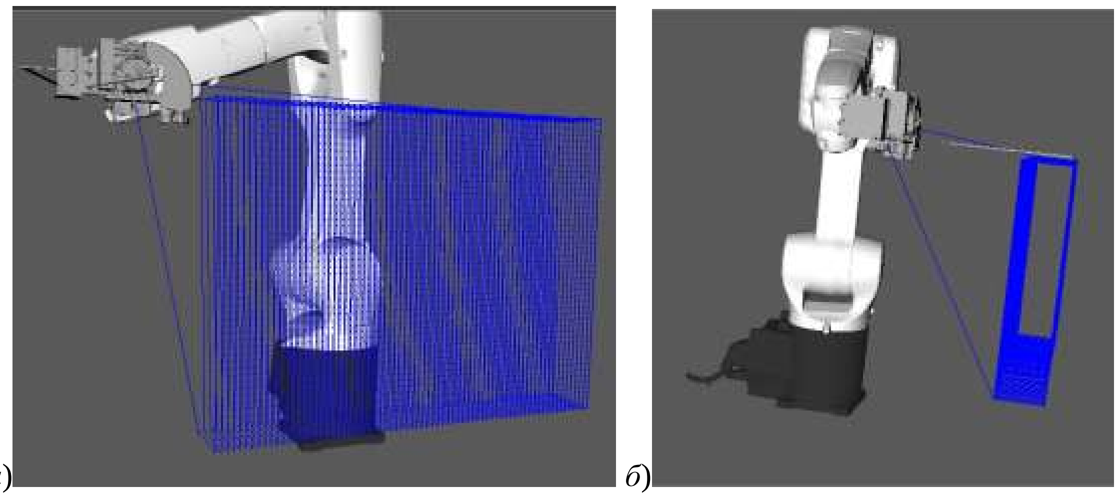


Figure 6. Scheme for determining the coordinates of welds

Using an array of the determined coordinates, a line describing the peak of the weld is created, for this the coordinates of the peak of the weld seams are approximated by a cubic smooth spline. The determined curves repeat the shape of the welds with sufficient accuracy, based on it, the points on which the trajectory of the scanning of the ECP is created are determined, Figure 7.



a) *б*)

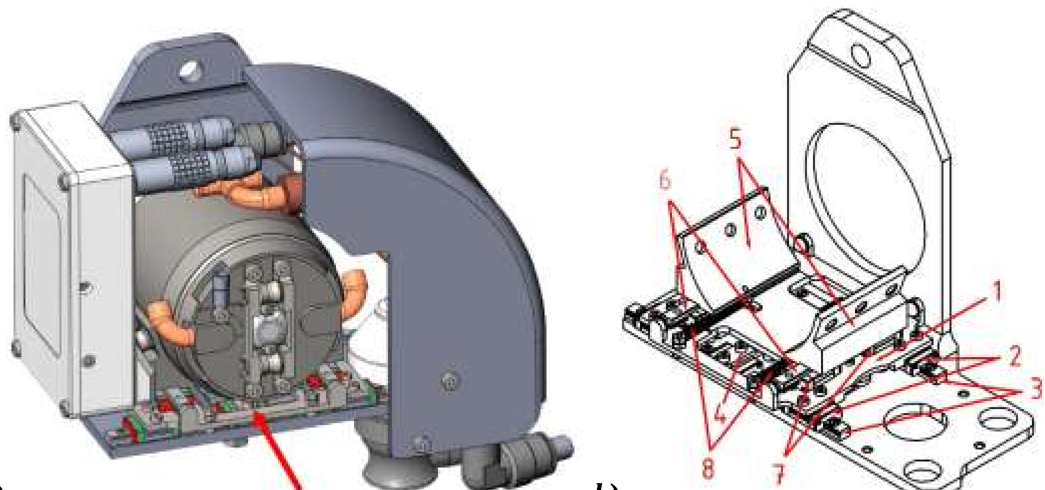
Figure 7. The trajectory of the robot manipulator, created using a laser profile sensor

6. Micro-displacement system of the eddy current probe

Since the approximating curve does not reflect short distortions of the shape of the weld (surges), it is necessary to provide additional degrees of freedom of movement of the ECP. To do this, the ECP is fixed to the robot's TJP through a micro-displacement system, which consists of two sets of linear guideways.

The micro-displacement system is located between the yoke of the ECP and the base attached to the TJP, Figure 8, (*a*). The design of the micro-displacement system is shown in Figure 8, (*b*). The intermediate support 1 moves along the rails 3 with the help of blocks 2. Supports 4 with springs and adjusting eccentric screws provide the initial point of positioning of the ECP in the direction across the axis of the ECP. The yoke of the ECP with a sensitive element is fixed on holders 5, on which rails 6 are mounted, which, together with blocks 7, ensure the movement of the ECP along the axis of the ECP, and springs 8 ensure its initial position and clamping to the weld.

The micro-displacement system ensures the movement of the ECP relative to the TJP in the direction perpendicular to the axis of the ECP in the range of ± 5 mm and along the axis of the ECP + 5 mm, as well as a fixed initial position, allowing the EPC to be setting on the weld in the initial position.



***a*)** ***b*)**

Figure 8. *a*) The location of the micro-displacement system on the ECP, *b*) the design of the micro-displacement system

7. Non-destructive testing procedure

The non-destructive testing procedure consists of the following steps:

- Installation of the RE in the welding and assembly equipment on the table using a bridge crane and positioning it on the table using deadlocks. After installing the RE on the table, the deadlocks are dismantled;
- Installation of a reference test piece on the welding and assembly equipment;
- Scanning of the reference test piece with a laser profile sensor, create of the actual trajectory of the scanning of the ECP according to the reference test piece;
- Scanning of the reference test piece using the ECP;
- Scanning of RE welds with a laser profile sensor, create of the actual trajectory of the scanning of the ECP along the RE welds;

- Drafting an automatic configuration report;
- Scanning of welds with eddy current probe;
- Making of a non-destructive testing report on one side of the resistive element;
- Turning the RE on the table with a bridge crane, repeating all the procedures for the second side of the RE;
- Drafting of the protocol of non-destructive testing of RE.

7.1. Drafting an automatic configuration report

When scanning a reference test piece with the help of a ECP, an automatic adjustment of the ECP is performed, which compensates for the wear of the ECP support system and other factors affecting the accuracy of measuring the depth of penetration of the weld. After scanning the RE welds with a laser profile sensor and create the trajectory of scanning the welds, an automatic adjustment report is drafting for the operator, which displays the settings of the ECP and its diagnostic signs. An example of the automatic adjustment report is shown in Figure 9.

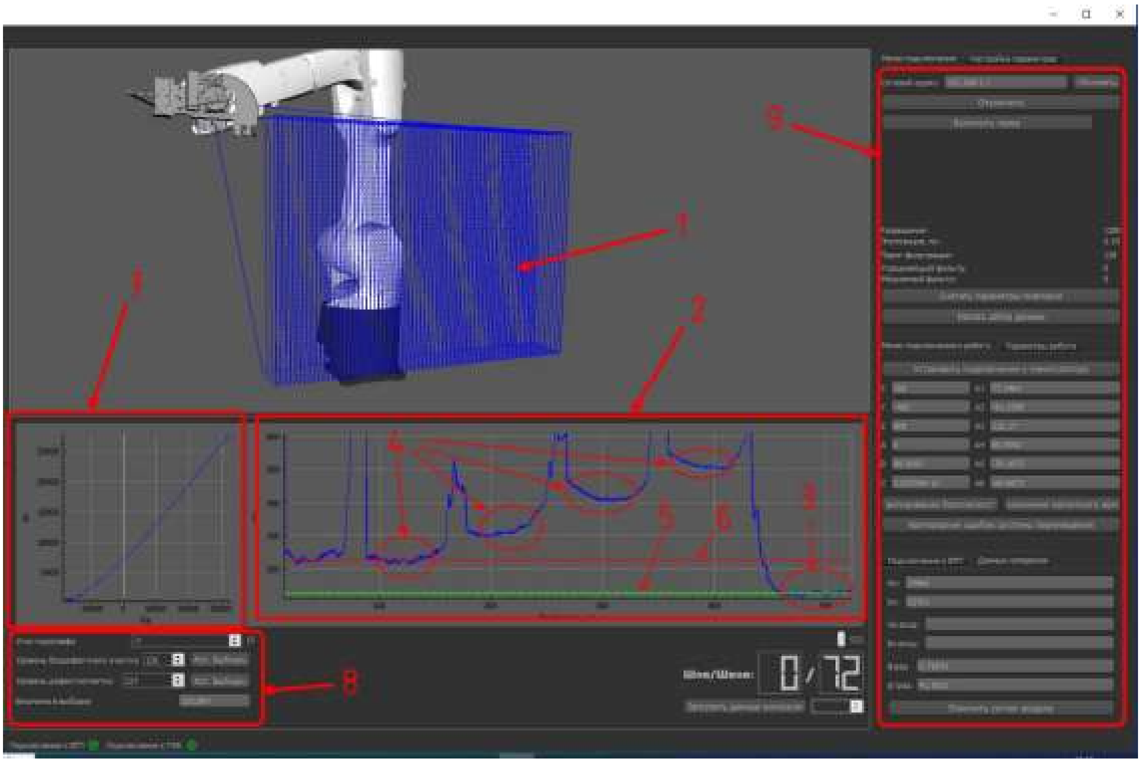


Figure 9. Example of an automatic adjustment report

In Figure 9, show: 1 – the created scanning trajectory of the welds, 2 – the scanning diagram of the reference test piece, which shows: 3 – the signal from the defect–free area, 4 – signals from artificial defects of various depths, 5 – the set level of the nominal depth of penetration of the weld, 6 - the level of defect marking. 7 – a complex plane that allows the operator to decipher the signals of the ECP in case of receiving an atypical signal. 8 – parameters of automatic adjustment of the ECP, 9 – a group of diagnostic parameters.

7.2. Scanning of welds

After receiving the report, the operator confirms the correctness of the created scanning trajectory and the correctness of the automatic adjustment of the ECP, after which the automatic scanning of the welds of the resistive element is started.
Upon completion of the scanning of the welds, a report is drafting containing the original signals of the ECP, which allows for a deep retrospective and statistical analysis of the testing results. An example of a report on one of the welds is shown in Figure 10.

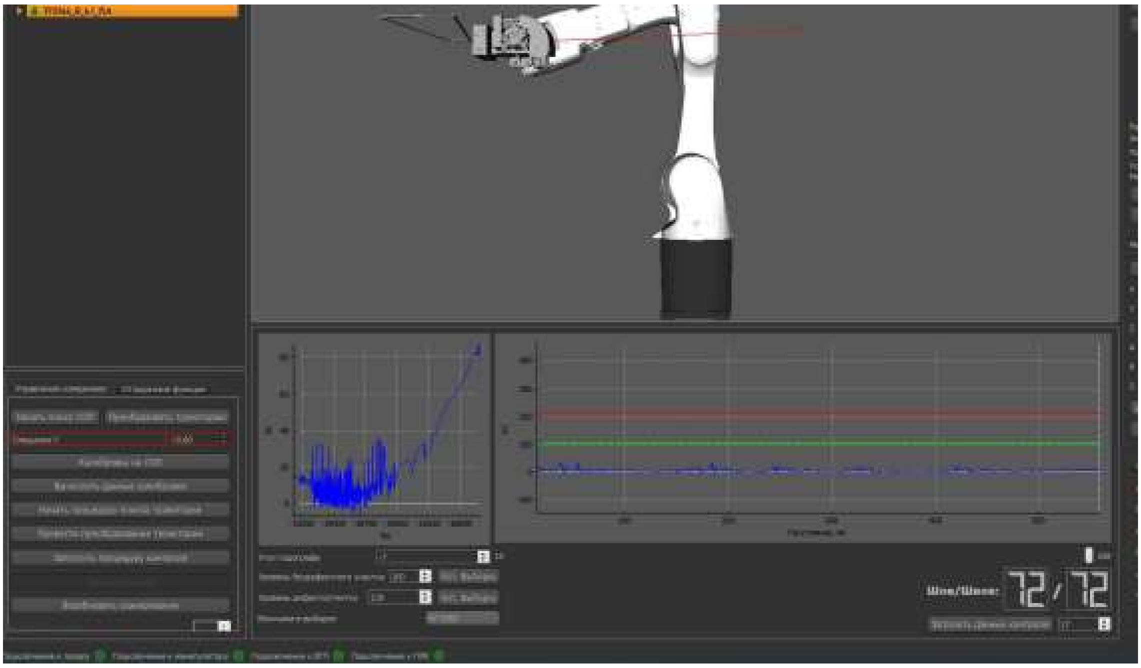


Figure 10. Example of a weld testing report

Upon completion of the scanning of the welds on both sides of the resistive element, a non-destructive testing protocol is automatically generated. The operator makes sure that it is correct, and then puts his personal signature.

8. Conclusion

The use of a laser profile sensor allows you to determine the actual shape of the test object. The use of a convolutional neural network in combination with simple geometric algorithms allows you to build a scanning trajectory of the ECP without operator intervention. Algorithms for automatic adjustment and creating of the scanning trajectory allow for automatic testing of resistive elements, however, an operator is needed to confirm the correctness of the results of automatic adjustment and to confirm the correctness of the results of non-destructive testing. In addition, the operator performs a number of procedures related to the installation, turning and removal of the test object to the test site.

References and footnotes

1. Vihretokoviy kontrol’ glubini proplavleniya torcevih svarnih shvov stalnyh plastin rezistivnyh elementov kommutiruyushey apparatury / P. V. Solomenchuk,

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