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Experimental Studies on the Evaluation of the Defectiveness of Weld Joints of the Main Parts of GTEs

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Abstract—Problems of the evaluation of the defectiveness of weld joints of the main parts of GTEs are considered. Experimental studies were performed and the optimal method for testing to accelerate the data sampling on detected defects was chosen.

Keywords: automated ultrasound testing, defectiveness of materials, weld joints, main parts of an engine, X-ray computational tomograph

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In order to provide the safe use of aviation gas turbine engines (GTEs) within aircraft-engine airworthiness standards the requirement to evaluate the "possibility of the destruction of a part within its approved life due to a defect in the material, in addition to assembly and operational defects" was introduced; i.e., one should verify the major parts [1–8] (primarily, parts made from titanium alloys, granulated alloys, and parts made by casting and welding) through the calculation of the probability of their destruction during operation, including those due to internal defects that were not revealed during nondestructive testing. To apply probabilistic calculation procedures, quantitative information on the presence of metallurgical defects in an item is required. In foreign countries, studies on the contents of metallurgical defects have been performed for many years, for example, for the blanks of titanium discs, plots are obtained of the suggested number of gas-saturated inclusions per 1000 pounds of alloy as a function of the size of these inclusions (ACC33.14-1 [9]). For this purpose, it was decided to perform research work to develop the main approaches to evaluate the defectiveness of materials using the experimental setup at FGUP VIAM, the OAO Aviadvigatel', and OOO ATG.

During these investigations, as well as via the study of the foreign normative documentation, a series of approaches was found whose use allows the quantitative evaluation of the defects in parts:

metallographic studies of polished sections (effective only for small defects);

spillage of the material melt through a network (to estimate the number of defects of the nonmetal inclusion type in some metals);

mathematical simulation of the blanking operation starting from casting (for deformable fireproof nickel alloys);

flotation of grains in heavy liquid (to estimate the number of nonmetal inclusions in disc blanks obtained by powder metallurgy);

statistical information storage on the defects that are determined during nondestructive testing.

Due to the fact that the studies described in this paper were aimed at parts that are obtained via welding [10–15], the metallographic studies of polished sections and statistical information storage on the defects determined by NDT at industrial companies were suggested as the principal approaches. The former is rather expensive; therefore, the second approach was chosen as the top priority, which is based on the determination of the number of defects that remain in a weld joint (that were missed during nondestructive testing) based on the accumulated statistical information on the defects (number and sizes) that were detected during nondestructive testing, as well as the known probability of their detection. The detection probability using the given approach is determined based on a special set of samples that were produced from the same material and according to the same technology as the test part. Works on the evaluation of the reliability of ultrasound testing have already been performed at FGUP VIAM [16–18]. The statistical data on the number of determined defects are gathered during multiple nondestructive testing, as well as during additional high-sensitivity studies, which allow an increase in the rate of data acquisition, but are

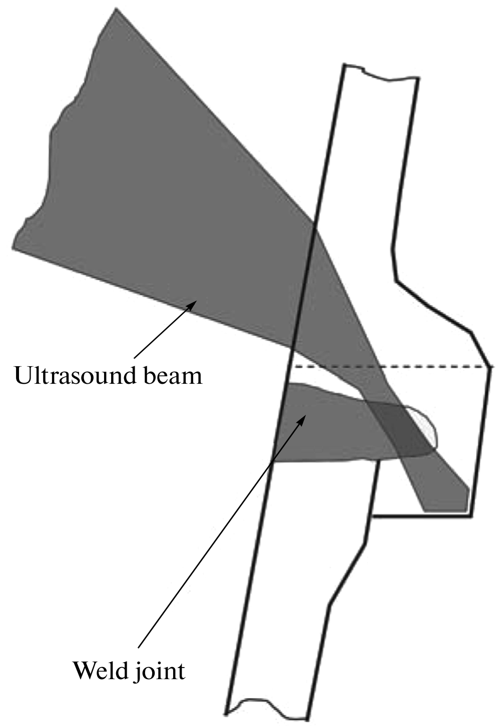

Fig. 1. A schematic representation of weld joint testing with the entry of ultrasound vibrations from a cylindrical surface.

not necessary to perform on each item and serve only for the accumulation of statistics, because rejection is performed according to the serial testing regulations. In addition, statistical data can be supplemented by the metallographic studies of items that were rejected according to the requirements of normative documentations, which is done during the multiple-testing technique.

As the test object that was used to develop the previously described approach and choose an alternative high-sensitive optional NDT method that can be used, for example, after the rejection of an item to obtain information on the content of internal discontinuities, the compressor drum of a helicopter engine that was past its life span was chosen. This drum is made from the VT8 titanium alloy. Its weld joints, which were made via electron-beam welding technology, were studied using various NDT methods, viz.,

the radiographic method using the multiple-testing technology that is used by industrial companies;

immersion ultrasound testing with the introduction of ultrasound vibrations from a cylindrical surface (as an optional NDT method);

immersion ultrasound testing with the introduction of ultrasound vibrations from a face surface that was obtained during the cutting of a drum in parallel to a weld joint (as an additional NDT method after item rejection at the test section).

The X-ray studies of the weld joints were performed using a RAP 150 M X-ray instrument by the preliminarily chosen optimal modes of radiographic control using an image-quality indicator based on Fe 13, Fe 14 iron. The testing was performed at a constant value of the anodic current $I_a = 80$ μA and constant anodic voltage $U_{\text{a}} = 80$ kV; the exposure time $t = 3$ min. The results of X-ray control showed more than 52 pores with sizes from 0.3 to 1.0 mm.

The studies using ultrasound vibrations from the surface of the cylindrical drum were conducted using an LS-500 LP ultrasound immersion system with a Panametrics V327 focused transducer with a central frequency of 10 MHz and a focus distance by water at 2.4 inches. The testing scheme is given in Fig. 1. To adjust the flaw-detective modulus, the test sample from a VT-8 alloy with the reference reflector (RR), which is equivalent in its reflective power to a flat-bottom hole that is 0.8 mm in diameter at the depth of 4 mm, was used. The adjustment of the flaw-detection modulus of the ultrasound immersion setup was performed as follows: the amplitude of the echo signal from the RR, which is equivalent to a flat-bottomed drill that is 0.8 mm in diameter at the depth of 4 mm, was 80% on the display of the flaw detector; the reporting limit (gate height) is 40 and 20% on the display of the flaw detector, the slope angle of the acoustic axis of the transducer relative to the normal to the surface of the cylindrical drum is 20 deg; this is equiv-

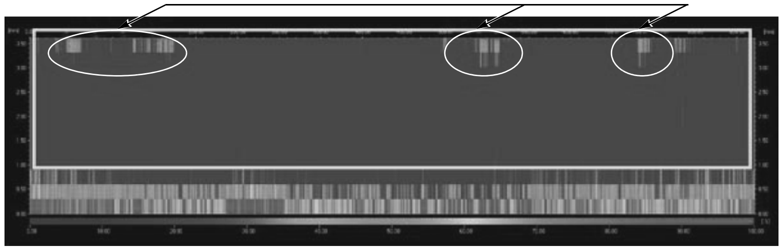

Fig. 2. The results of ultrasound testing of the weld joint zone from a cylindrical surface as a sweep of type C.

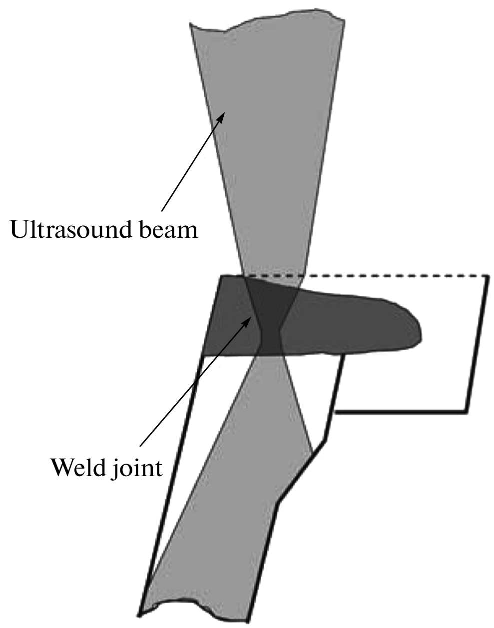

Fig. 3. A schematic representation of the testing of a weld joint with the entry of ultrasound vibrations from a planar face surface (the dashed line indicates the flat entry surface).

alent to the entry angle of shear ultrasound vibrations to a test object of 45 deg; and the distance from the face of the transducer to the entry of ultrasound vibrations in a test object along the ultrasound beam propagation is 32 mm. The results of the studies revealed and recorded the zones with an elevated echo-signal amplitude (Fig. 2), whose origin was then determined.

To perform ultrasound testing by compressional waves in the axial direction, the drum was cut by individual rings containing weld joints; a planar face surface of entry with a roughness of less than *Ra* 1.25 was formed. The scheme of the testing is given in Fig. 3.

The adjustment of the flaw-detection modulus of the system was performed by analogy with the entry of ultrasound vibrations from a cylindrical surface at the distance by water from the transducer face to the entry surface $WP = 55$ mm. The studies showed a set of anomalous zones with an increased amplitude of the echo signal (Fig. 4), which were missed by two previous NDT methods. For this reason, the most promising method for the statistical data storage for the determined small discontinuities was presumably this NDT method.

According to the results of the studies using all three NDT methods, the detected anomalous zones were classified by two types:

the first type of zone was detected by all three testing methods;

the second type was detected only by ultrasound testing with the entry of ultrasound vibrations from the face surface.

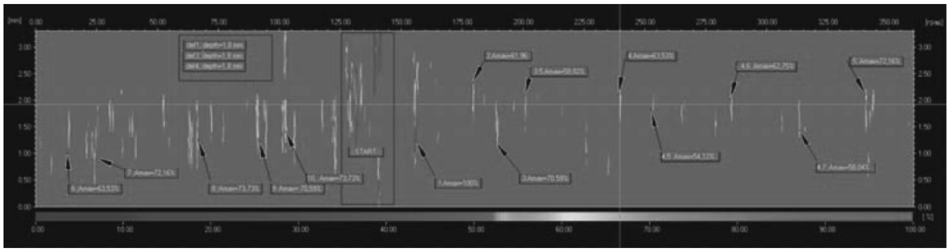

Fig. 4. The results of the ultrasound testing of the weld joint zone from a planar surface as a sweep of type C.

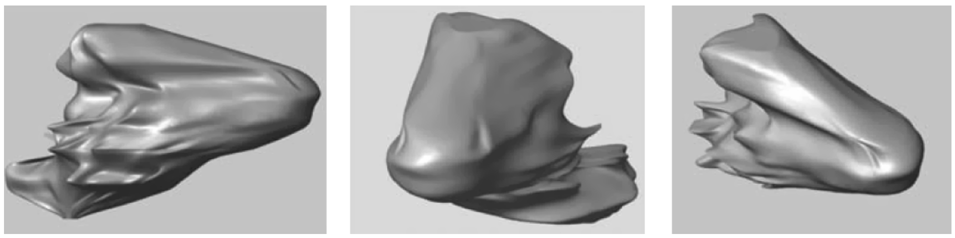

Fig. 5. 3D A model of the reduced three-dimensional image of the defect surface.

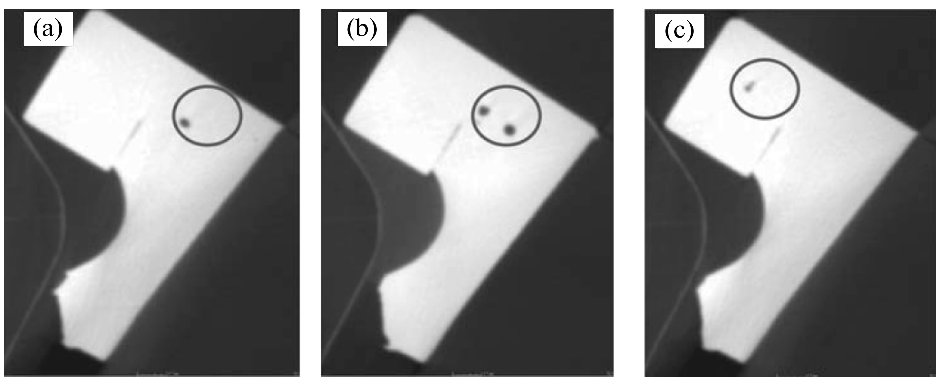

Fig. 6. The results of testing weld samples using an X-ray computational tomograph: (a) a defect missed by standard NDT methods that was detected only using the tomograph, (b) a defect detected by ultrasound testing, and (c) a defect that was missed by standard NDT methods and detected only using the tomograph.

In order to determine the identity of the appearance of anomalous zones, as well as in the case of the detection of discontinuities and their size measurement, metallographic studies and studies using an X-ray computational tomograph were performed.

The metallographic studies of the weld joint samples were conducted in the suggested locations of defects by consequent removal of metal layers on a Tegramin-25 grinding machine (Struers Co.). The preliminary grinding (smoothening of the surface) was performed on a SiC-Pap#320 wheel at the rate of 300 rpm and an effort of 30 N; and the final polishing was performed on an MD Piano #220 wheel at the rate of 150 rpm and an effort of 30 N copolishing 50 μm at each cycle. During the polishing, a DP-suspension M 9 μm lubricant was used as the cutting compound.

The outlook and defect size after each cycle of removal of a metal layer that was 50 μm in thickness was recorded on a Leica DM IRM optical microscope; the image recording was performed using a VEC-335 digital camera (three megapixels); the section panoramas were recorded using the Image Expert Sequencer 4 image-stitching program; the preparation of images for the quantitative analysis and their mathematical treatment was performed using the Image Expert Pro 3x program. It was determined from the results of the metallographic studies that in all the anomalous zones, there were internal discontinuities with sizes of $228 \times 80 \times 150$ to $878 \times 585 \times 800$ μm. In Fig. 5, an example of a recovered three-dimensional image of a defect surface is given using the SolidWorks program complex from the results of the records of 16 sections.

It was determined using the results of X-ray studies that were performed using a Nikon Metrology XT H 450 high-sensitivity computational tomograph with a record of the testing results on a digital flat-panel detector for the industrial nondestructive testing (Perkin Elmer XRD sensor panel) that in the given preliminarily cut anomalous zones, in addition to defects, there were many discontinuities with negligible sizes, which were missed by the three NDT methods (Fig. 6). Therefore, this method showed the best results as an alternative method for the acceleration of data acquisition on the content of internal discontinuities in an item.

Thus, these studies showed that the most complete flaw detection in weld joints is provided by computer tomography. When it is not possible to perform computer tomography on an engine-building enterprise, flaw detection by immersion ultrasound testing using a focused high-frequency transducer is possible. The method of metallographic studies with subsequent recording of layers was successfully used to determine the exact shapes and sizes of determined defects. The results that were obtained in this work could be used during the development of an industrial procedure for the quantitative evaluation of the defectiveness of the weld joints of the main parts of GTEs.

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