

Development of Methods of Ultrasonic Testing of Materials and Welded Metal Structures at the E.O.Paton Electric Welding Institute

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Abstract. Progress of computer engineering led to development of all-purpose microprocessor flaw detectors, the functions of which are provided by program means, which may be complemented by many special functions, for instance, defect representation in three projections, producing holographic and tomographic images, producing patterns of fine defect distribution, etc.

These components were used by the E.O.Paton Electric Welding Institute to develop unique technologies of detection of defects of the type of oxide films, which are practically plane, but are crack initiators, and of very accurate determination of plane defect dimensions. The method of acoustic synthetic aperture was used to develop a procedure of determination of precise dimensions of inner defects of different shapes. Methods to evaluate fine defect clusters are important for plants in long-term service. Evaluation of a cluster of fine “admissible” defects is an absolutely new direction in evaluation of the life of metal structures in long-term service. Fine “admissible” defects grow together with time, so that their admissibility cannot be regarded separately from the large number and location of these defects.

Oxide films and compressed lacks-of-fusion are one of the defect types, which are the most difficult-to-detect by UT. Detection of such defects is complicated, because the amplitudes of echo-signals reflected from them and from a sound weld section are commensurate. This technology is being successfully introduced for testing joints produced by flash-butt welding and for arc welding of non-ferrous metals [1].

The E.O.Paton Electric Welding Institute of the NAS of Ukraine developed an all-purpose automated multi-channel system for controlling the process of testing and automatic processing of the results of weld UT. System operation is controlled by a computer by a program providing selection of the main parameters of the system, namely number channels and sequence of channel switching on, delay and duration of gate signals for each channel, values of the coefficients of echo-pulse amplification, etc., with calculation of the detection threshold, determination of conditional dimensions, location and kind of the defect. All the necessary information is displayed. In addition, testing results (quantity, location, conditional dimensions, kind of defects) are printed out to obtain the test protocol [2].

Developed system of automated UT can be used to solve the following problems: detection of weld defects across the entire section (allowing for the thickness of the material being welded); determination of the kind of defects and their location.

The test protocol states the values of adaptive detection thresholds for each channel; channel numbers, through which the echo-signal, exceeding the adaptive threshold, arrived (these data allow determination of the depth of defect location: bottom, middle, top);

current co-ordinate of the defect along the weld from the point of testing start; conditional length of the defect on threshold level in each channel; curves of distribution of echo-signal amplitudes along the weld in each of the channels. Information about control results is recorded and stored.

Defect classification in keeping with the processing algorithm is performed as follows. At simultaneous exceeding of the amplitude of echo-signals of the respective adaptive thresholds in the channels of transducers connected by “tandem” schematic and isolated combined transducer a decision is taken that this is a discontinuity-type defect. At exceeding of the adaptive threshold just in the tandem channel this is a defect of oxide film type. When the threshold is exceeded in the channel of an isolated combined transducer these are fine inclusions arranged in the bulk (lens).

Control of products from structural ceramics was performed at the E.O.Paton Electric Welding Institute using an acoustic microscope, the block-diagram of which is given in Fig. 1.

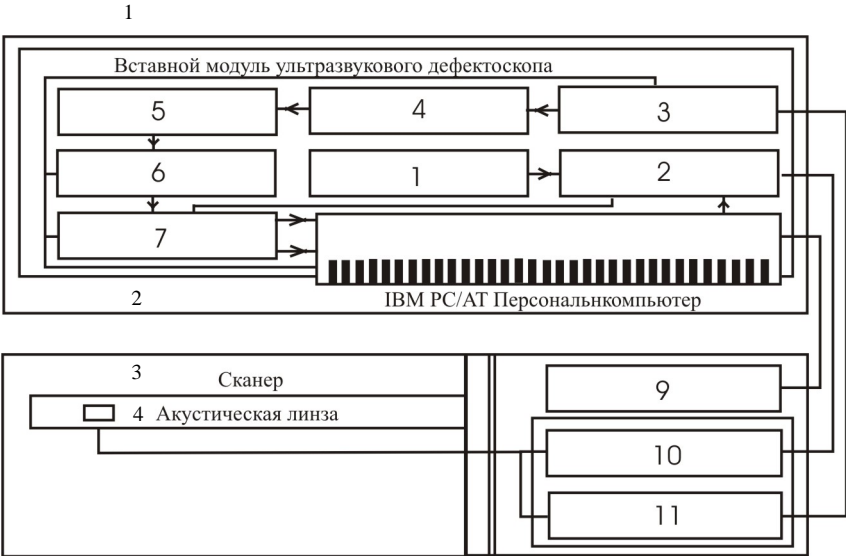


Fig. 1. Scanning microscope block-diagram: 1 – quartz oscillator, 2 – functional generator; 3 – HF amplifier; 4 – input key; 5 – demodulator; 6 – amplifier; 7 – ADC; 8 – computer interface and registers for step motor control; 9 – step motors; 10 – power amplifiers; 11 – preamplifier.
 1 – plug-in module of ultrasonic detector; 2 – IBM PC/AT personal computer; 3 – scanner; 4 – acoustic lens

Here a PC is used as the controlling computer, which assigns the parameters of the receiving and transmitting circuits of the high-frequency block, controls object scanning and simultaneously constructs the image in keeping with the amplitude of the received signal or its time characteristics. The entire radio-frequency circuit of the flaw detector, except for the remote block of the pre-amplifier, is made as a standard plug-in computer module [2]. Working range of ultrasonic frequencies of the flaw detector is from 5 to 50 MHz, range of measured time intervals being from 20 ns to 80 mcs. Software allows readily performing setting up and adjustment of the acoustic circuit of the flaw detector and the scanning system. It is also possible to plot images of type A and B, as well as C type, depending on the amplitude and delay time of the received ultrasonic pulse. In addition, the flaw detector can be used for measurement of the velocity of Raleigh surface wave with up to 0.2% accuracy. Scanning field of the microscope-flaw detector is equal to 120x300 mm. Scanning step is measured by the program in the range of 0.05 to 0.5 mm. Sample scanning is performed by moving an acoustic lens along it. Flaw detector is fitted with a set of lenses with working frequency from 5 to 50 MHz. A quartz rod is used as the acoustic guide, on one side of which is the acoustic lens with 20° to 60° aperture and on the other side is an

ultrasonic transducer, which is a plate from lithium niobate piezocrystal, plugged on the other side with a damper based on hallium paste with tungsten filler.

Flaw detector allows detection of microcracks and discontinuities of an area larger than 1000 μm , if crack opening is greater than 100 \AA with the resolution of 0.05 mm in the scanning plane and 0.02 mm across the depth at the location depth from 0.1 to 5 mm and more, depending on sample material. Examples of flaw detector application are given in Fig. 2 and 3. Fig. 2 shows C-scans produced at UT with longitudinal waves of frequency $f = 40$ MHz of fragments ($0-90^\circ$) and ($90-180^\circ$) of a ceramic bushing from silicon nitride of diameter $D_n = 33$ mm; ID = 15 mm at 0.8 mm depth. Delamination 1 in the form of a light zone, as well as fine pores 2, are clearly visible in the Figure. Light circular regions correspond to the pore image, and grey areas fringed by dark zones, are images of hard alloy inclusions.

Results of UT of a Si_3N_4 plate 100 mm long, 20 mm wide and 4 mm thick are given in Fig. 3. The image shown in Fig. 3a, was obtained at a higher detection sensitivity, than that shown in Fig. 3b. Dark circular regions correspond to local inclusions of a hard alloy.

Fig. 3b shows an image of a composite material, which is a “puff-pastry”, consisting of boride fibres 100 μm and aluminum matrix. White bands are visible, which correspond to boride fibres. Control was performed at frequency $f = 25$ MHz with focusing at the depth of 0.3 – 0.5 mm. A computerized multifunctional Zip-scan instrument was used to control thick ceramic plates (10 – 40 mm). The instrument has high-capacity hardware and software means for acquisition, storage and representation of the data. It enables storing the signal shape with a resolution and real-time data processing. The instrument can implement the TOFD method, and SAFT modes, allowing improvement of the accuracy of measurement of the horizontal size of the defect and its co-ordinates, and of the precision of defect images due to increase of the signal-to-noise ratio.

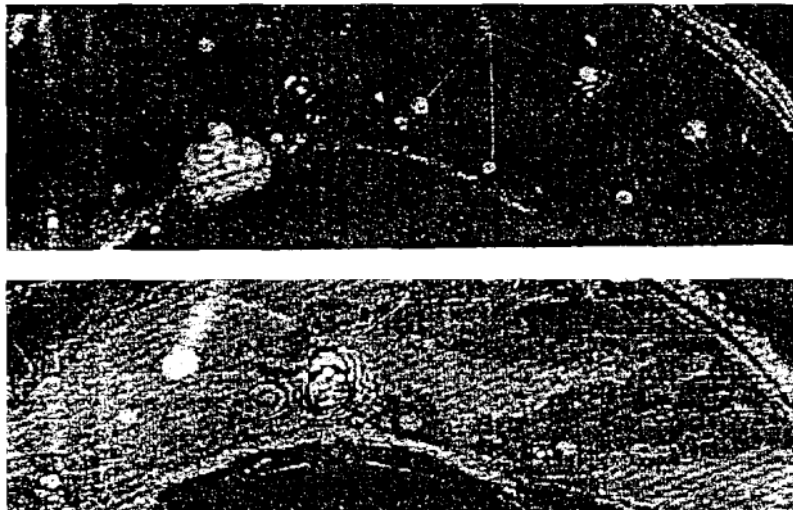


Fig. 2. Visual representation of ultrasonic scanning of the ceramic plate: C-scan produced at UT of a ceramic bushing fragment ($0-90^\circ$); C-scan of a ceramic bushing fragment ($90-180^\circ$).

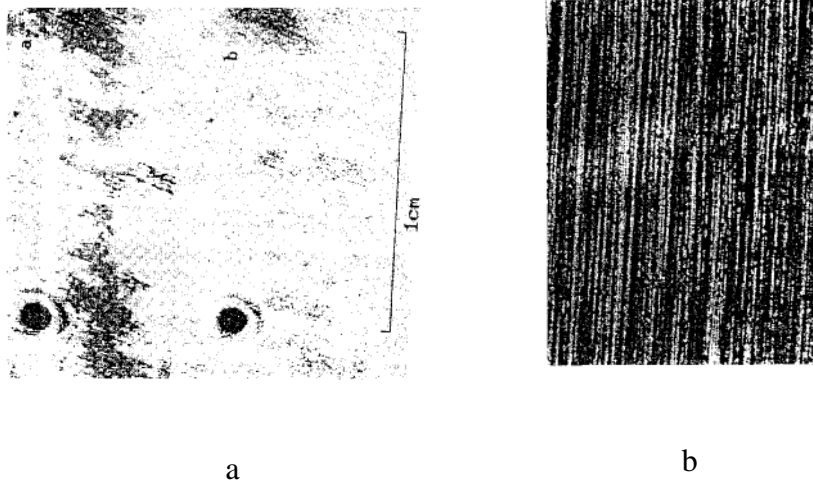


Fig. 3. Visual representation of ultrasonic scanning: a – image of a ceramic plate; b – ultrasonic image of a composite material

When ceramic parts (substrate for PC boards, bushings for friction pairs, discs, lining of pistons, rotors, turbo superchargers) were studied with this flaw detector, Lamb waves, surface, head and bulk ultrasonic waves were used in the frequency range of 1 – 10 MHz.

Experiments were conducted in the pulsed-echo mode and using the TOFD method.

Fig. 4a shows a C-scan, produced at testing of a ceramic plate. Dark zones are images of cracks, parallel to the plate surface in a 2 to 5 mm layer by depth. B-scan, corresponding to ultrasonic scanning with a transducer at 5 mm distance from the plate edge is given in Fig. 4b, which shows the images of cracks in a 2 – 5 mm layer at 30 mm distance from the plate edge and up to 55 mm. Signals from sample surface and backwall reflection are observed in a defectfree area (0 – 30 mm). In the defective zone of 30 – 55 mm signals from a crack are observed, which shield the backwall reflection.

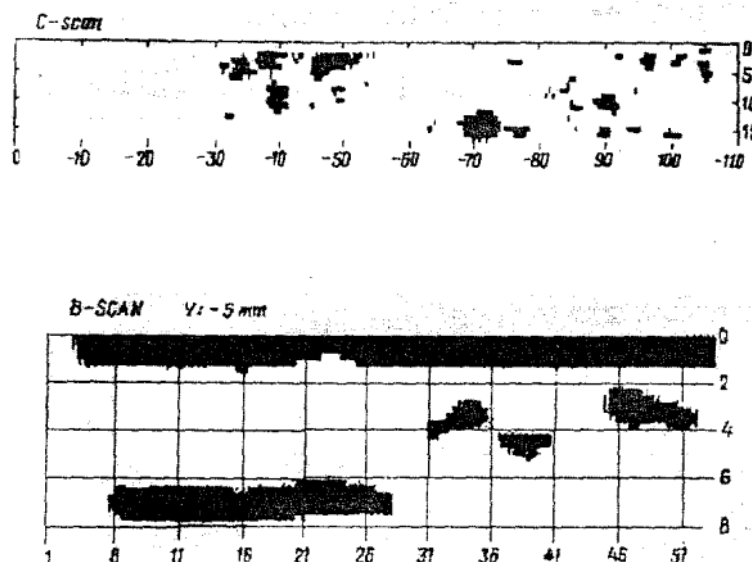


Fig. 4. Visual representation of ultrasonic scanning of a ceramic plate: C-scan produced at ceramic plate control; B-scan produced at UT of a ceramic plate.

The conducted systematic studies of the capabilities of high-frequency acoustic instruments in the field of ceramic part control showed that:

- defects of 10 - 15 μm length are reliably detected, when using single-focus focusing transducers, operating at frequencies of 50 – 80 Hz, at location depths of up to 1 mm;
- defects of 20 – 150 μm size are reliably detected in 1 pass, when using two-focus TR transducers, operating at frequencies of 40 – 60 MHz at depth of 1 to 6 mm;
- defects of 150 - 500 μm are reliably detected, when using computerized ultrasonic flaw detector “Zipsan-3” at up to 40 mm depths;
- measurement of phases of signals reflected from the tested sample surface and inner reflectors enables determination of the nature of delaminations, inhomogeneous inclusions and cavities in parts from Si_3N_4 , AlN , and Al_2O_3 .

Technology of determination of precise dimensions of inner defects by the synthetic aperture methods (SAFT) should become widely accepted in the next few years. This is a method of simulation of a wide-range focusing beam of an ultrasonic transducer by digital processing of amplitudes of signals obtained by scanning with a regular unfocused beam. We will show that SAFT has technological advantages compared to regular focusing transducers, which should have different focal distances.

The main idea of SAFT method is illustrated in Fig. 5.

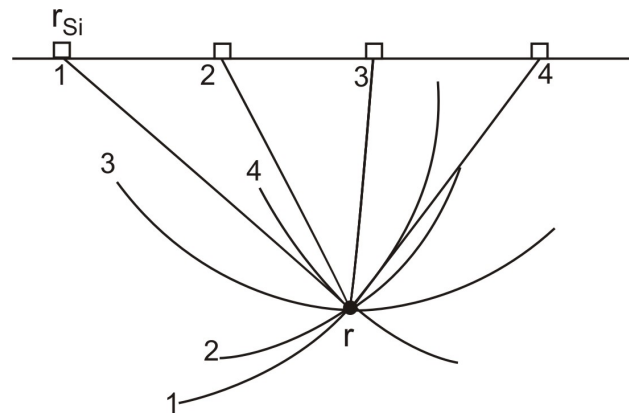


Fig. 5. Illustration of SAFT principle. Arcs of the circumference show the possible position of the reflector at the given position of the receiver.

If a transducer sends a δ -pulse in angular region α , then reception of reflected signal at moment of time t_0 means that the inhomogeneity can be located in any point on an arc of radius $\gamma_0=2t_0C_0$ with the center in the transducer zero point. Arcs plotted at different positions of a transducer, intersect in the point of transducer location. Thus, superposition of signals $S(t, \gamma_{Si})$, $i = 1, 2 \dots n$ will yield an increase of image level in the transducer location. Applying such a procedure to all points of space, we obtain, in this case, an image of a section of the object of control along the line of transducer displacement (B-scan).

Image quality deteriorates both at longer duration of the pulse and at decrease of angle α and number of zero points.

To implement the principle of image restoration by SAFT methods, an automated ultrasonic system was developed. Its block diagram is shown in Fig. 6 [3]. Obtained data were processed in a computer, allowing for the geometrical characteristics of the object of control.

To improve the validity and adequacy of the recorded inhomogeneity, PET scanning is conducted at difference angles of incidence (this actually increases the range of α angle aperture) for respective transducer k . Let us illustrate the effectiveness of the suggested UT system by two examples of images that are plotted by the traditional and SAFT methods.

During planned UT of a welded joint on the principal central pipeline of a NPS, a discontinuity was found, having a reflection area several times larger than the limit

admissible value. Conditional dimensions by height were also higher than the specified values. Attempts to size the defect were unsuccessful. In particular, it was not possible to establish by traditional techniques, whether the discontinuity is cracklike or 3D. Using a

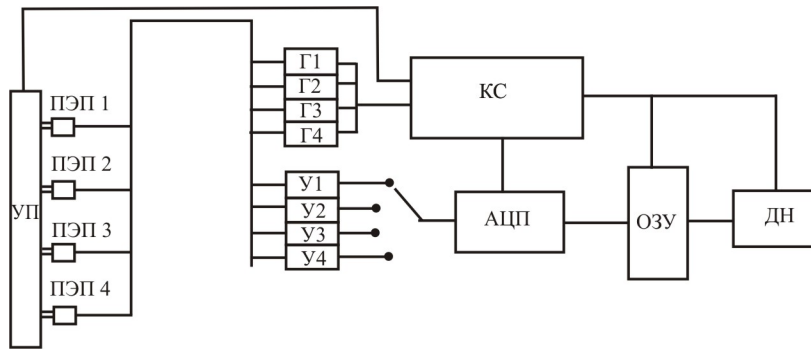


Fig. 6. Block-diagram of a system to implement the SAFT method.

Symbols:

- PET – piezoelectric transducer;
- DD – device of PET displacement and positioning (scanner);
- G1 – G4 – ultrasonic pulse generators;
- U1 – U4 – electric signal amplifiers;
- SC – system controller;
- ADC – analog-digital converter (10 digits, 8-30 MHz);
- RAM – storage (buffer);
- DS – disc storage.

computerized system, which provided mechanical scanning, positioning of transducers and storage of control data on electronic carriers, it was possible to connect and analyze the control results for different types of transducers, and also perform mathematical processing of the data by SAFT method [3].

Ultrasonic testing of the entire welded joint was performed by PET with angles of incidence of 0° , 45° and 60° (4 MHz) into the metal. Fig. 7 gives a visualization of the result of ultrasonic scanning of a welded joint section, plotted by the traditional method, without mathematical processing of the data, and Fig. 8 is the mathematical reconstruction of the discontinuity location by the SAFT method.

Thus, analysis of all the testing data enabled determination of the nature and exact location of the discontinuity, i.e. SAFT reconstruction allowed localizing the reflection region and precisizing its location. The actual kind and location of the discontinuity is shown in Fig. 9, which was obtained at opening of this zone of the pipeline welded joint.

UT of a welded joint of a separator in petroleum processing production can be given as the second example.

The discontinuity was detected during performance of scheduled testing. Equivalent area of discontinuity reflection is equal to 19.6 mm^2 , this being significantly higher than the admissible level for welded joints 70 mm thick (formally not more than 7 mm^2). Conditional height of the discontinuity is 29.2 mm. As the discontinuity was assessed as inadmissible, and quality repair of the welded joint of such a great thickness is very difficult to perform in terms of technology, the question of the actual dimensions of this discontinuity became urgent.

Fig. 10, 11 gives the result of visualization of the discontinuity for different levels of representation (sensitivity). Difference in assessment of the discontinuity height is more than 200%. Therefore, it does not seem possible to determine the discontinuity height with

an acceptable accuracy, suitable for strength analysis based on the traditional methods of visualization.

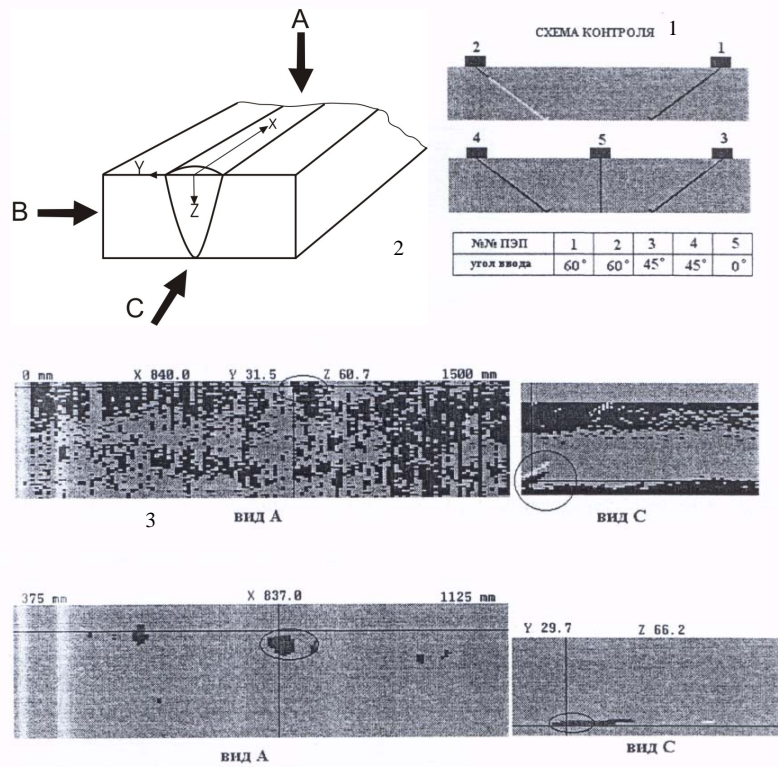


Fig. 7. Traditional visualization of the results of scanning NPS central pipeline.

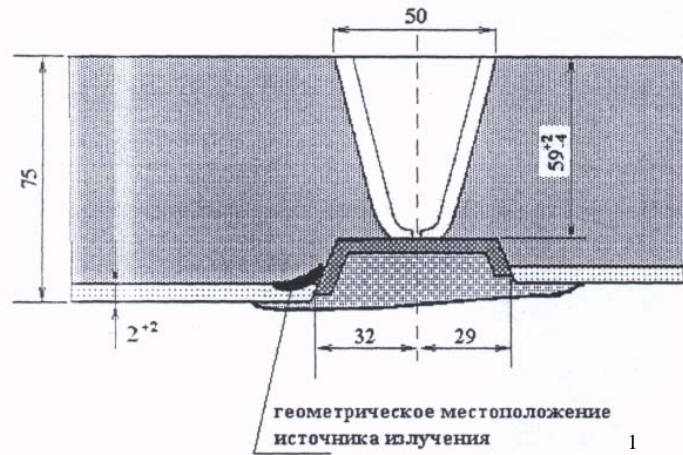


Fig. 8. Result of calculation and plotting of the pattern of reflection source location by SAFT method.
1 – geometrical location of the radiation source

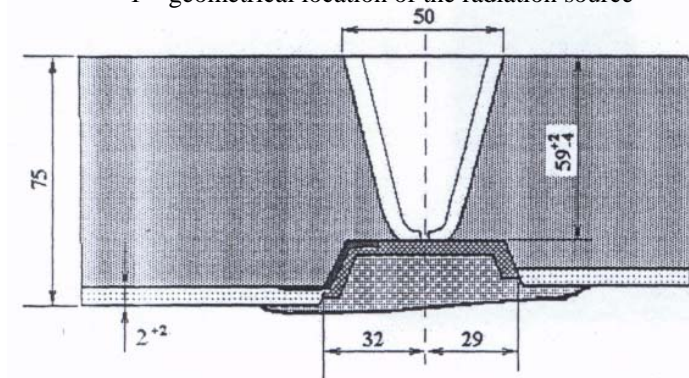


Fig. 9. Actual appearance of the discontinuity in the welded joint by the opening results

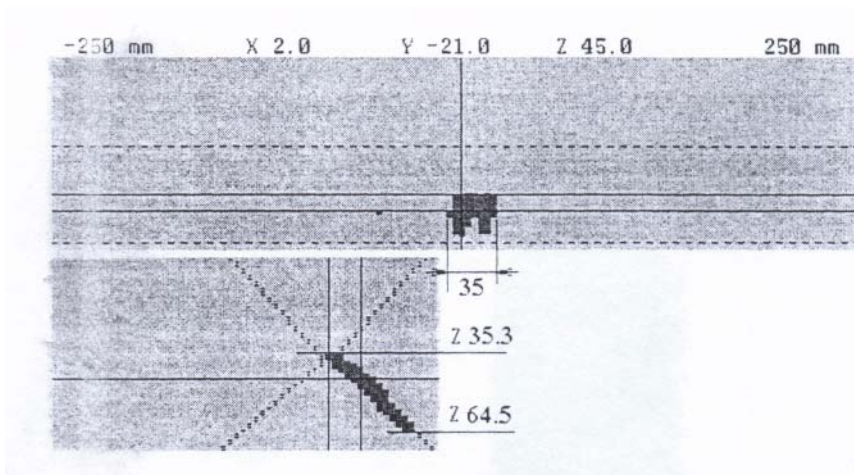


Fig. 10. Visualization of a discontinuity in a separator at the control level of sensitivity.

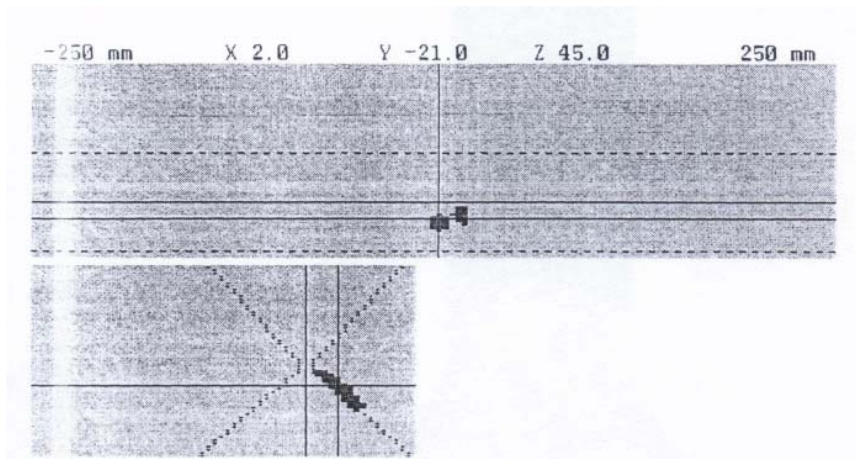


Fig. 11. Visualization of a discontinuity in a separator on the rejection level of sensitivity.

SAFT method was used to calculate the discontinuity dimensions by height. Processed results and their visual representation are shown in Fig. 12. As follows from processing data, precised dimensions of the discontinuity (by height) are equal to $8.7 \approx 9$ mm.

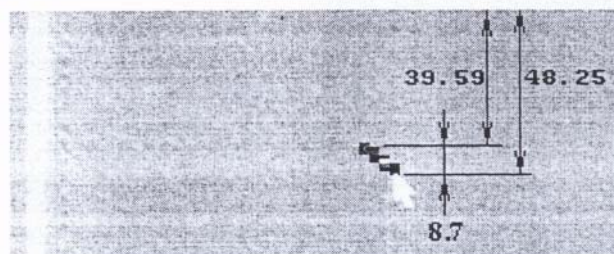


Fig. 12. Result of processing UT data by SAFT algorithm.

Work on automation of non-destructive testing, including ultrasonic testing, is traditional for the E.O.Paton Electric Welding Institute of NASU. Automatic systems for UT of the main oil and gas pipelines and other pipe typesizes have been operating for many years in different countries. Recently the E.O.Paton Electric Welding Institute developed, manufactured and introduced at OJSC “Khartyszsk Trubni Zavod” (KhTZ) systems for automated ultrasonic testing (AUT), namely NK-204 and NK-205. NK-205 unit is a multi-

channel AUT system and allows detection of defects in the weld and near-weld zone (NWZ) on pipes with up to 25 mm wall thickness, and detection of defects of a longitudinal and transverse orientation with recording of the test results.

The problem at UT consists in the procedure of defect identification by their location in the weld, shape and dimensions, as well as separation of the defects of the weld and near-weld zone (NWZ), considering false signals (acoustic and electric noise, signals from reinforcement bead, etc). Under these conditions manual testing (MAUT) is used in order to precise the nature of the defect in case of a discrepancy between the results of AUT and X-ray TV inspection (RTC). While AUT is being improved in terms of increasing the validity of determination of the most hazardous defects, allowing for defects of the near-edge zone, the technology of arbitration MAUT is saturated by elements of computer engineering, application of more sophisticated methods of the type of TOFD, SAFT, etc. These technologies allow determination of the dimensions and location of plane defects with a greater precision (up to fractions of mm).

The E.O.Paton Electric Welding Institute has been working on the electromagnetoacoustic (EMA) method recently to address the problems of weld UT. Work conducted at Kremenchug Pumping Station showed the good prospects for EMA method application for UT of pipes in the main pipelines. Contactless EMA method of UT does not require a thorough cleaning of the surface and allows generation of ultrasonic oscillations, which cannot be induced using piezoplates [4].

Various types and designs of electromagnetoacoustic transducers (EMAT) were used to optimize the NDT procedures, namely for thickness measurement – EMAT with a permanent magnet for excitation and reception of shear waves with angle of incidence of 0^0 ; for NDT of welded joints and sheets – EMAT with a quasi-constant pulsed magnetization, which excites and receives Lamb waves, as well as SH-waves. On aluminium and steel samples of 1 to 200 mm thickness (250x250 mm size) the error of thickness measurement was ± 0.25 mm, and in the range of 7 – 200 mm it was ± 0.1 mm. Investigation of the influence of the size of clearance between the transducer and surface of the controlled sample with a non-conducting coating (based on epoxy resin) 0.1 – 0.5 mm thick showed, that the clearance size considerably influences the signal amplitude.

At coating thickness of 0.1 – 0.3 mm the accuracy of sample thickness measurement already was ± 0.5 mm.

Experiments on detection of defects in sheets and welded joints using Lamb waves (S_0 and S_1 modes) were conducted on samples of steel 4, 5 and 8 mm thick. Focusing EMAT exciting and receiving Lamb waves, were used in testing steel samples of 100x300 mm size and 4 - 5 mm thickness, as well as welded joints. Artificial defects (reflectors) were detected, equivalent in their reflection ability to a slot 20 mm long, 0.5 mm wide and 0.4 mm deep. It should be noted that an actual defect of 4 mm² area and 0.3 mm depth was quite reliably revealed at scanning of a sample from two sides. In a sample made in the form of a shell (520 mm diameter and 8 mm thickness) with a weld on the circumference, lacks-of-penetration in the weld root were reliably detected at the depth of 3 - 5 mm. Experiments were conducted at the frequency of 1.25 and 2.50 MHz.

Transverse waves of SH-polarization were used to conduct research on a working sample from welded pipes of 720 mm diameter and 10 mm thickness with artificial and natural defects.

Thus, experiments revealed that:

- 1) EMAT exciting and receiving shear waves at an angle of 0^0 , are effective for measurement of the thickness of aluminium and steel products; the error of thickness measurement in the range of 2.5 – 200.0 mm was not greater than ± 0.25 mm, and the error of measurement of thickness of a sample with 0.1 - 0.3 mm thick coating was ± 0.5 mm;

2) EMAT exciting and receiving Lamb waves (S_0 and S_1 modes) can be used to advantage for detection of defects in sheet structures and welded joints. Artificial defects with the reflectivity equivalent to that of a slot 20 mm long, 0.5 mm wide and 0.4 mm deep, as well as lacks-of-penetration in 8 mm thick welded joints at 3 – 5 .. depth were revealed with a high degree of reliability. Experiments were conducted at the frequency of 1.25 to 2.50 MHz. It is shown that in this case it is rational to use the working frequency of 1/25 MHz.

3) it is rational to use EMAT exciting and receiving horizontally-polarized and transverse waves (SH) when testing items (in particular, pipes and welded joints) with a coarse surface, as well as in the presence of the remnants of insulation, and foreign layers. Actual defects of a round shape, extended and short defects of different orientation were reliably detected at the frequency of 1 MHz, angle of incidence of 75^0 and focal distance of 230 mm.

It should be noted that an advantage of EMAT for space applications is the ability to perform testing in a wide range of temperatures ($-150 \dots +170^0$) without use of couplants or excitation of various types of waves, in particular, SH-polarization. These waves cannot be excited by piezoelectric UT transducers. The main advantage of SH-waves consists in that they can be used to test sheet structures and welded joints, located under a sheathing, contaminated surfaces without emptying the plant, testing large areas, without scanning the surface with the transducer, but just fastening it in accessible areas.

The E.O.Paton Electric Welding Institute of NASU is developing technologies and means of highly-efficient low-frequency ultrasonic testing (HUT) of extended plants during their operation, such as insulated pipes, supported pipes or pipes under road covering.

Normal waves have the longitudinal, bending and torsional modes, and may be used to reveal defects extending circularly and (or) axially in the pipe. These waves may be excited and received in sheets or pipes?? at the frequencies of 20 - 200 kHz at a distance of 5 – 50 m. It should be noted that HUT is sensitive to a combination of the defect depth and width (area). HUT means are pulse-echo flaw detectors, providing information on the location and approximate size of the reflector, measured in percent of the pipe cross-section.

Investigation of test samples showed that the least metal loss detectable with HUT means, is equal to approximately 3% of pipe cross-section [5].

Acceptable reject level is achieved, if signal amplitudes equivalent to 9-10 % of the pipe cross-sectional area are recorded.

Special low-frequency multi-channel circular arrays have been developed. These arrays consist of a set of ultrasonic transducers, special electronic multi-channel modules for exciting, receiving and processing signals, which are connected to a computer performing processing and representation of defect responses.

Traditional means of UT of thickness and construction of patterns or “maps” of corrosion damage, which use 1 – 10 mm range of wave length, require having direct access to the entire tested scanned surface of the plant. Thus, insulated, underground or otherwise inaccessible metal structures are difficult to control by the traditional UT echo-methods without conducting expensive preparatory operations to make the plant (for instance, pipe) accessible for UT.

Using HUT large sections (5 to 50 m long) can be scanned from one position of ultrasonic transducer block. These means allow testing the entire thickness of the pipe wall for tens and hundreds of meters in one measurement. The E.O.Paton Electric Welding Institute developed a multi-channel instrument, including ultrasonic transducers with the capability of adjustment of the frequency and angle of UT wave incidence, generator, receiver and electronic modules, allowing selection of the required frequency of oscillations and displaying of UT results on a PC. Selection of the necessary angle of incidence and UT oscillation frequency enables exciting the most effective modes of normal (controllable)

waves to detect artificial and actual defects in the bulk of pipes of 110 – 250 mm diameter with 6 – 12 mm wall thickness.

A pipeline 48 m long, 6 mm thick of 114 mm diameter (Fig. 13) was mounted for experimental verification of the instrument operability.

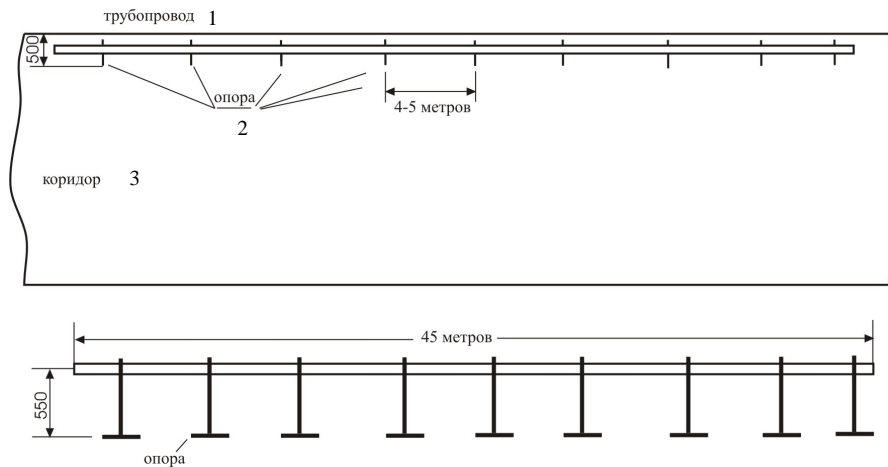


Fig. 13. Test pipeline
1 – pipeline; 2 – support; 3 – corridor

Results of an experiment to detect an artificial reflector – a 2 - 3 mm deep slot of the length of $\frac{1}{2}$ of pipe circumference are shown in Fig. 14.

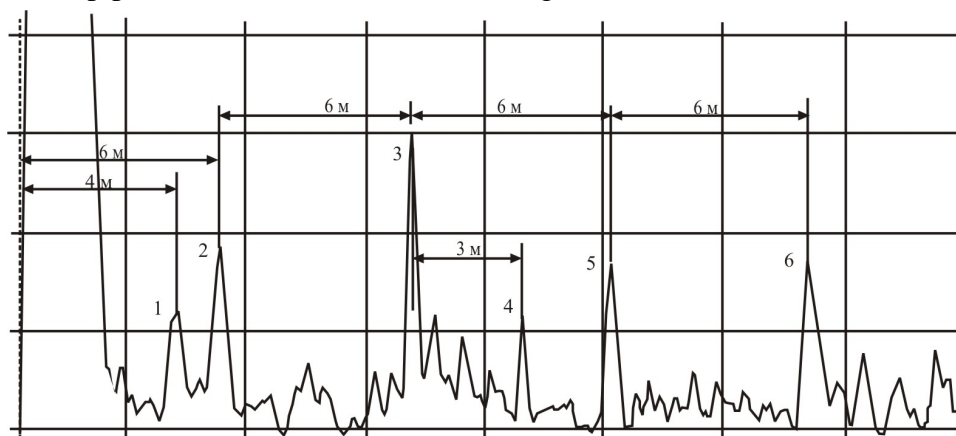


Fig. 14. Results of conducting an experiment to detect a pipe wall thinning: 1, 5 - signals from a slot at the distance of 4 and 15 m from pipe ends; 2, 3, 4, 6 – signals from pipe welded joints.

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