ULTRASONIC INTROSCOPY OF WELDED JOINTS FOR NUCLEAR ENGINEERING

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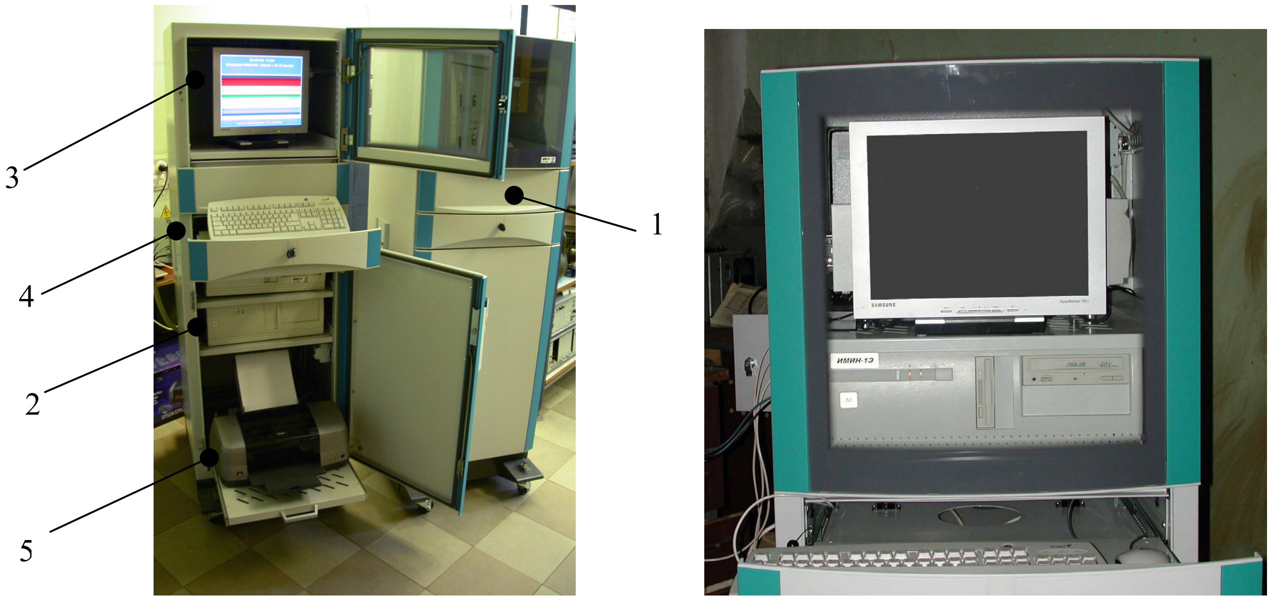
The ultrasonic introscopy takes on special significance for quality monitoring of welded joints. This report deals with the experience of a creation and an employment of multipurpose single- and two-channel ultrasonic introscopes. These introscopes have been designed and manufactured in the Bochvar Institute of Inorganic Materials. The introscopes are used for automatic testing of various types of welded joints with the wall thickness of 0.5-10 mm. The introscopes differ both in the number of channels and in the construction. The two-channel introscope "IMIN-2S" is shown on the Figure 1.a. This introscope connected to a display is placed in a sealed cabinet. Such design allows the introscope to be used in plant conditions. The Figure 1.b shows a desktop introscope "IMIN-1E" developed for lab conditions. The introscopes are PC-based hardware-software complexes. The introscopes operate at the frequency range of 10 - 50 MHz using pulsewidths of 20 - 50 ns. The introscopes control scanners on which test specimens or test parts and piezoelectric probes (PEP) are fixed. The scanners have steppers providing a reciprocating motion of PEP and a rotation or a movement of test parts. The Figure 2 shows a functional block diagram of a two-channel introscope.



(a) (b)

Figure 1. a – two-channel introscope IMIN-2S: 1 – sealed cabinet; 2 – introscope units; 3 – display; 4 – shelf with a keyboard and a mouse; 5 – printer; b – introscope IMIN-1E.

Besides the conventional ultrasonic images (A-scan, B-scan, C-scan) the algorithms of new types of ultrasonic images (a layer-by-layer image and a "sum" image of sections) have been implemented in these introscopes.

To obtain a layer-by-layer ultrasonic image (T-scan), software splits a tested zone into layers by a transit time of ultrasonic signals, analyzes the combination of signals in each layer and carries out the quality assessment according to a pre-set algorithm [1]. After that, ultrasonic images reconstructed from these codes are displayed. Depending on a weld penetration an image can be yellow (excessive penetration) or red (unacceptable incomplete penetration). The image is green for a mi-

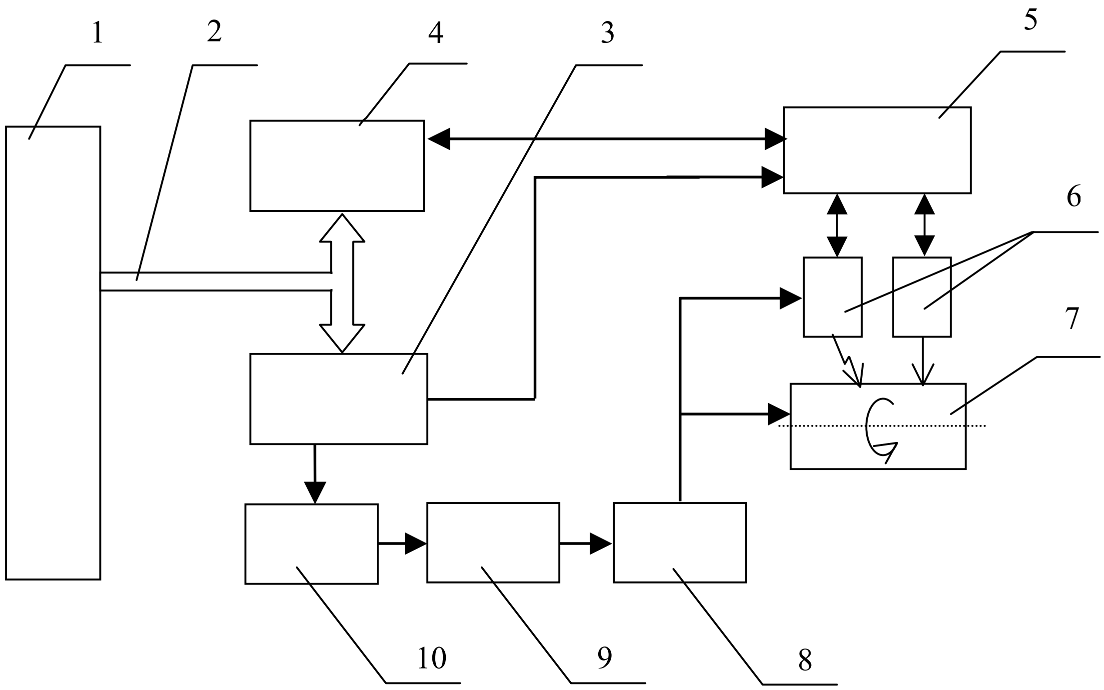


Figure 2. Block diagram of two-channel introscope. 1 – PC; 2 – PCI-bus: 3 - control card; 4 – ADC; 5 – two-channel generator and amplifier; 7 – piezoelectric probes (PEP); 8 – scanner; 9 – stepmotors; 10 – stepmotor control unit.

nor technologic incomplete penetration. The results of scanning of Plexiglas samples of a butt weld are shown in the form of the B-, T-scans on the Figure 3. One of the T-scan modifications is applied for a testing of edge joints of stainless-steel elements. The Figure 4 shows the scheme of insonification (a) and the images of its results (b). The scanner provides a rotation of a test part and a movement of PEP above its surface across a joint weld on the length of 15 mm with a step of 0.5 mm. During the testing only 3 selected zones are analyzed on the base of which an ultrasonic image is created. As because of a weld joint wobbling the detected signals change their travel time, the gate automatic synchronization mode has been developed. Then the estimation of signal distribution is carried out layer-by-layer and T-scan ultrasonic images are displayed (Figure 4 (b)). On the ultrasonic images following color codes are used: blue for an acoustic baffle, red for a joint weld, green for an internal surface of welding parts. The obtained ultrasonic images allow to estimate a penetration of edge joint with an adequate accuracy. The measuring accuracy of penetration **L** is less than 0.3 mm when the welded parts thicknesses are up to 4 mm. Thus, an NDT inspector can easily estimate the quality of all weld through the utilization of the T-scans. While testing various types of welded joints, the more detailed defect identification is obtained by the B-scan, which gives a possibility to estimate the depth of a reflector (defect). Besides, some defects that are located near the back surface (e.g. incomplete penetration up to 0.1 mm, excessive penetration, welding of backing strap) become much more apparent. However, the B-scan supplies an image of only one cross-section of weld. Hence, the image pictures imperfections located in the slice with the thickness equal to a diameter of ultrasonic beam.

To produce an ultrasonic image of the full volume of a weld, it is necessary to integrate the data of all slices. It is possible, if linewise scanning is replaced by scanning by sine curve with a range equal or more than the thickness of the weld (Figure 5). When performing the linewise scanning it is also possible to connect the end of one line with the beginning of the next one using software. The step of scanning along a weld must to be less than or equal to 0.7d in both modifications. The method of the imaging of results, picturing an ultrasonic image of the full volume of a testing zone, is named the “LB-scan”.

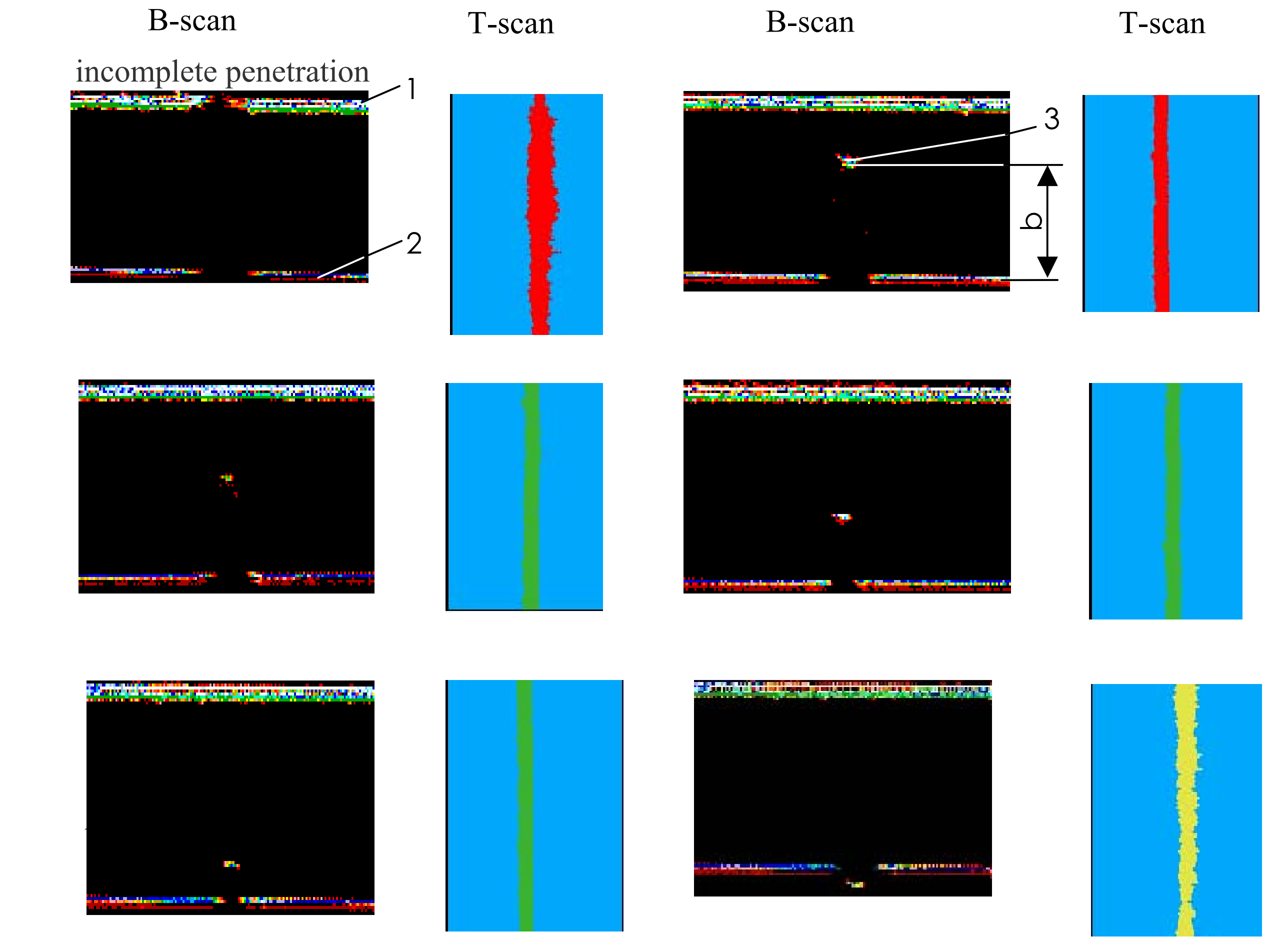
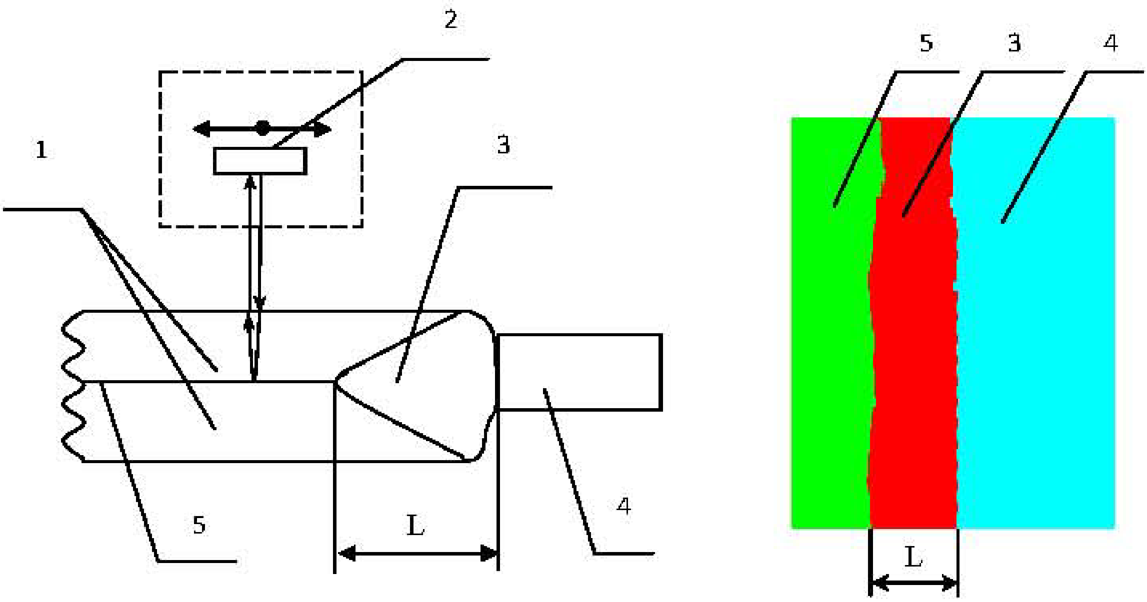


Figure 3. The ultrasonic images of the simulator of an incomplete penetration.1 – front simulator surface; 2 – back simulator surface; 3 – ultrasonic image of a top of an incomplete penetration; b – size of incomplete penetration; ■ - acceptable weld penetration; ■ - unacceptable weld penetration; ■ – excessive penetration.



(a) (b)

Figure 4. a – scheme of insonification; b – ultrasonic image; 1 – welded parts; 2 – piezo-electric probe (PEP); 3 – weld; 4 – acoustic screen; 5 – internal surface of welded parts; **L** – depth of penetration.

Impulses reflected by the sample's front surface are used for synchronizing a separation of impulses reflected by its back surface. To reconstruct the ultrasonic image the amplitude and the time coordinate of the maximum impulse into the gate are measured. The thickness of lines imaging the front and the back surfaces of the sample and the imperfections is compressed to one pixel. This enables to raise considerably the resolution when measuring the depth of the weld penetration. The LB-scanning method unites an easy adjustment of acoustic path and control reliability.

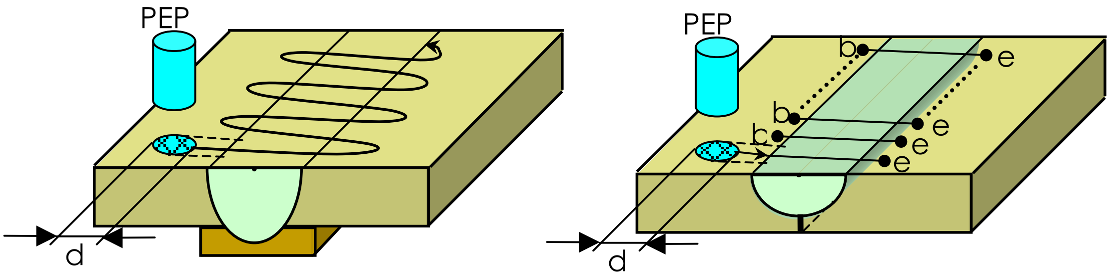


Figure 5. d – ultrasonic beam diameter; b – beginning of scan; e - end of scan.

The Figure 6 shows LB-scans of samples of weld with a backing strap (a) and with an incomplete penetration (b). For thin-wall constructions (0.1 to 0.5 mm) with two or more acoustic interfaces that are used for a testing results recording (e.g. a weld joint with backing strap), a C- and T-scanning time separation of pulses reflected from all surfaces and internal sag of cast metal is carried out with an accuracy of 40-100 ns. An LB-scanning time separation accuracy is 4-6 ns. Thus, the LB-scanning considerably simplifies instrumentation adjustments and the scanner's construction and increases the testing reliability.

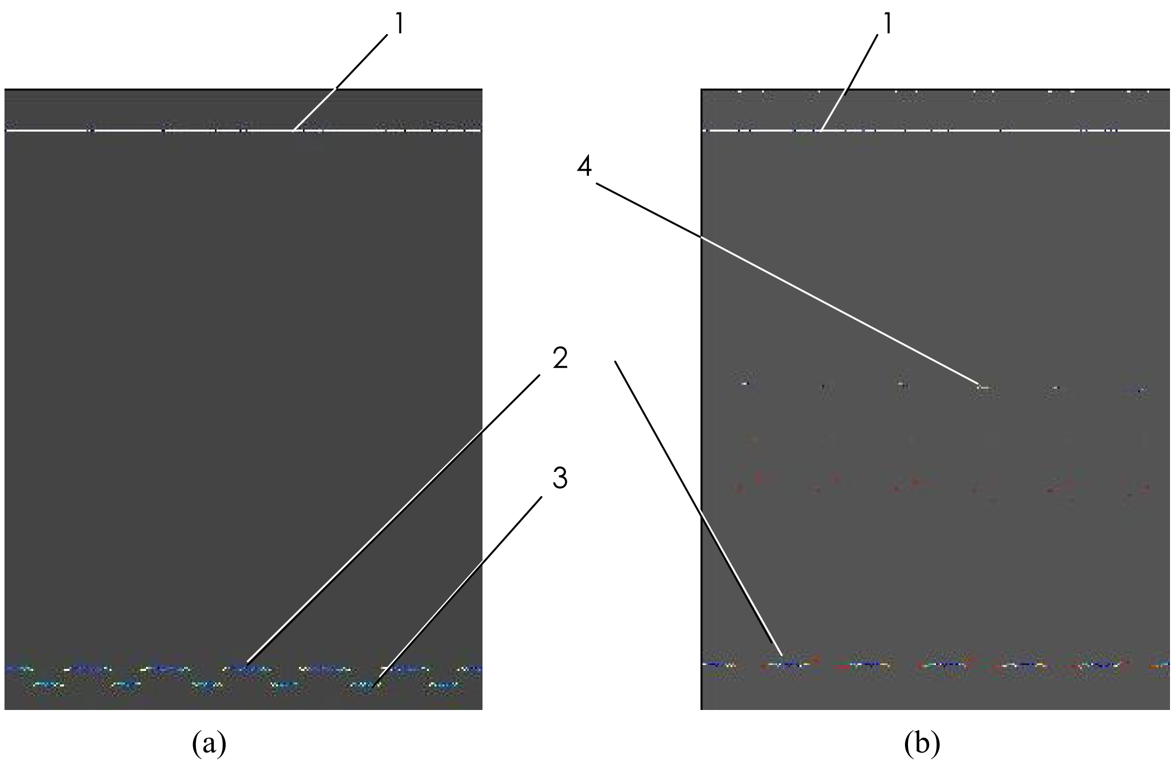


Figure 6. LB-scan: 1- image of front surface; 2 – image of back surface; 3 – image of backing strap; 4 – image of incomplete penetration.

There are two channels with a direct probe (PEP1) and an angle probe (PEP2) automatic switching in «IMIN – 2S» that are to enforce its testing reliability. When using PEP1 to define the depth of an incomplete penetration, there is a reflection of longitudinal wave ultrasonic pulses from the top of the incomplete penetration if its size $\boldsymbol{r}$ is more than $\boldsymbol{\lambda/2}$ (where λ is a wavelength). Using focalizing PEP1 with $\boldsymbol{r} > 60$ µm a reflection of pulses from the top of the incomplete penetration is registered. The weld depth ($\boldsymbol{h}$) is determined as $\boldsymbol{h = t{\cdot}c/2}$, where $\boldsymbol{t}$ is a travel time of the ultrasonic pulse and $\boldsymbol{c}$ is a sound velocity. When a value of $\boldsymbol{c}$ is known $\boldsymbol{h}$ can be defined precisely enough (5-10%) by a measured $\boldsymbol{t}$. If a size of the top of the incomplete penetration is $\boldsymbol{r < \lambda/2}$, then $\boldsymbol{h}$ is evaluated by the amplitude of a signal reflecting from lateral areas of the incomplete penetration, that is with the help of an angle PEP2. In this case, an error of the measurement of $\boldsymbol{h}$ by signal amplitude is more significant (for thin-wall parts it can reach up to 25-80%). The Figure 7 shows a scheme of insonification of the two-channel testing.

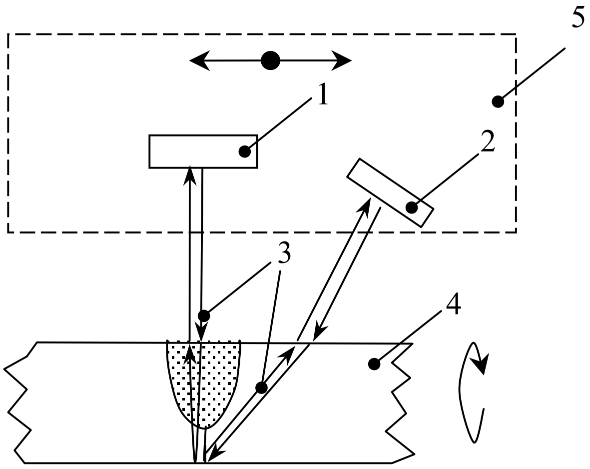


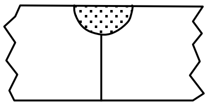
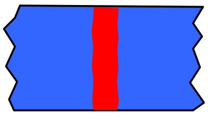
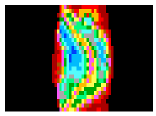
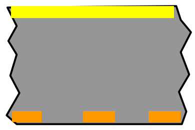
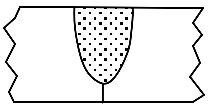
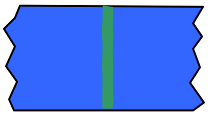
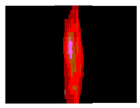
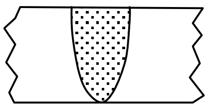
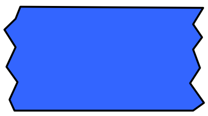
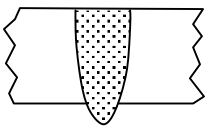
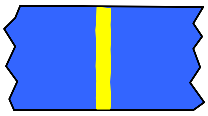
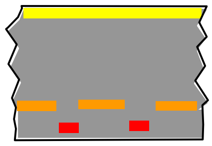
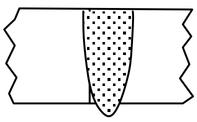
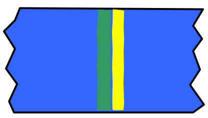
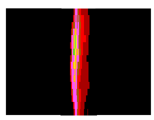
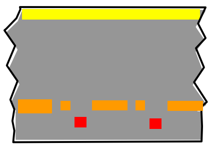
Figure 7. 1 – PEP1; 2– PEP2; 3 – ultrasonic beam; 4 – sample; 5 – unit of PEP.

The scanning is performed linewise with the step up to 0.5 mm. The simultaneous motion of the unit of PEPs and the test parts is made by stepmotors. The ultrasonic beam input coordinates are stored. The introscope "IMIN-2S" reconstructs the ultrasonic images of the T- and the C-scans using the coordinates of reflected signals, their amplitudes and their time coordinates. During the testing process the both ultrasonic images (bars) are created simultaneously. The left bar shows the T-scan and the right bar shows the C-scan. The schematic representations of normal cross-sections of investigated weld joints are shown in a table below. The butt welds are presented in the Table 1 and the butt welds with backing strap are presented in the Table 2. The ultrasonic images for each section are shown. The ultrasonic images of the T- and C-scans performed for butt welds enable to define a presence and types of defects, as well as the depth of the penetration of the weld. The C-scan images from the second column of the Table 1 are auxiliary to the T-scan images when taking a decision concerning the quality of a weld. The LB-scan is a main mode of testing of butt welds with backing strap. The images of the Tables 1 and 2 represent, in fact, a catalogue for quality estimation of weld joints. Using these ultrasonic images, an NTD inspector can identify a defect rather quickly, thus his task becomes much simpler. Besides, the human factor (an NTD inspector's skill) is practically eliminated.

A method [2] is offered for a butt weld. This method is based on the simultaneous scanning of a direct probe (PEP1) and an angle probe (PEP2) across a weld with a step less than an ultrasonic beam diameter. The ultrasonic beams emitted by the PEP1 and the PEP2 intersect on the level of a defined weld penetration. The path of scanning and the method of an image reconstruction supply a continuous serial record of 2D images of all testing zone sections. The signals received from PEP1 are used to reconstruct the locations of the front and the back surfaces, the technologic incomplete penetration, the top of penetration. They are pictured on every image in the form of color lines. The received signals from the PEP2 are used to reconstruct a direct-to-scale curve with points corresponding to the travel time of the pulses reflected from the top of penetration zone.

The Catalogue of Ultrasonic Images of Butt Weld.

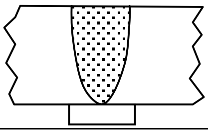
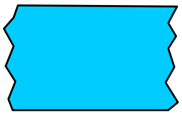
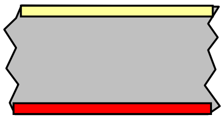
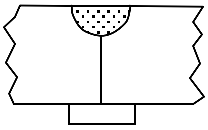
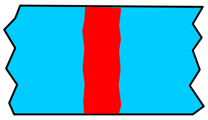
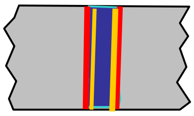
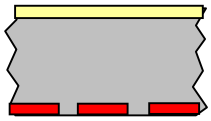
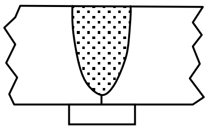
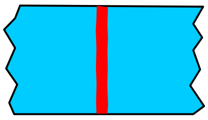
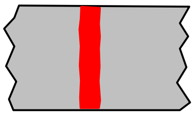
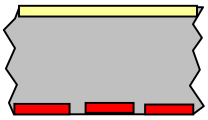
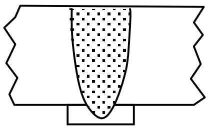
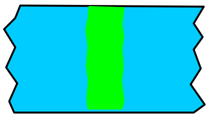
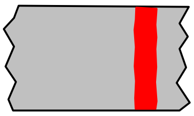
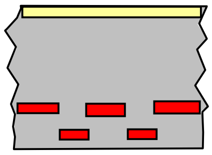
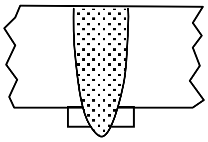
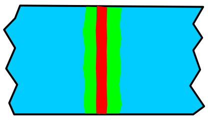
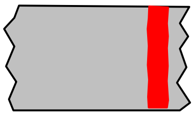
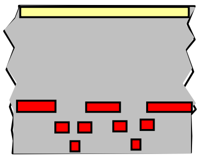
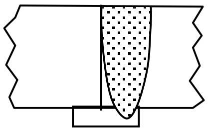
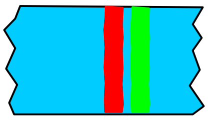
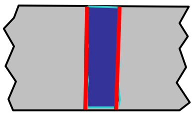
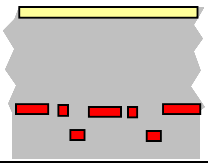
The table 1

№	Section of of a weld joint	Ultrasonic Images			Weld quality evaluation
		T-scan Channel 1	C-scan Channel 2	LB-scan*	
1					The depth of a weld penetration is much less than the width of the part. A defect.
2					The depth of a weld penetration is less than the width of the part. It's a minor incomplete penetration A weld is normal.
3					The depth of the weld penetration is equal to the width of the part. A weld is normal.
4					The depth of a weld penetration is more than the width of the part. A defect.
5					A weld penetration is deeper than normal. The cast zone of the weld is shifted relative to the butt. A defect.

* - Ultrasonic images of 2 lines are presented in the LB-scan column.

The Catalogue of Ultrasonic Images of Weld Joints with Backing Strap.

The table 2

№	Section of of a weld joint	Ultrasonic Images			Weld quality evaluation
		T-scan	C-scan	LB-scan*	
1					The depth of a weld penetration is equal to the width of parts. A weld is normal.
2					The depth of a penetration is much less than the width of the part. A defect.
3					The depth of a penetration is slightly less than the width of the part. A defect.
4					The depth of a weld penetration is more than the width of parts, but it does not go below the backing strap. A weld is normal.
5					A penetration is deeper than normal. A defect.
6					The depth of a weld is normal, but the cast zone is shifted relative to the butt. A defect.

* - Ultrasonic images of 2 lines are presented in the LB-scan column.

The point of maximum amplitude of this curve is marked in a different color. The Figure 8 presents the scheme of the testing method described above by the example of the scanning of tube butt weld joint. The scanner provides the axial rotation of a tube and the reciprocating motion of PEP's unit across a weld. The ultrasonic image of the sequence of testing zone sections "summed" by two channels (LB-scan) is presented in the Figure 9.

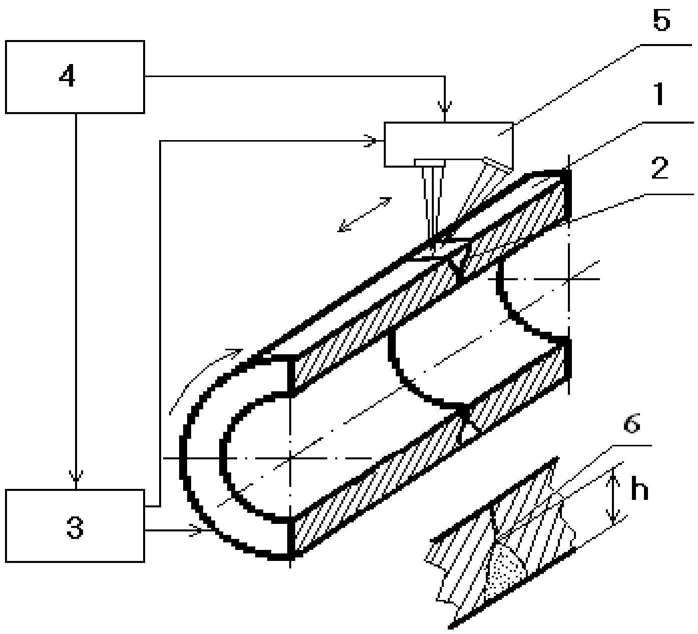


Figure 8. The example of the two-channel testing. 1 – tube with weld; 2 – weld; 3 – scanner; 4 – ultrasonic introscope; 5 – unit of PEP1 and PEP2; 6 – top of a incomplete penetration; h – depth of weld.

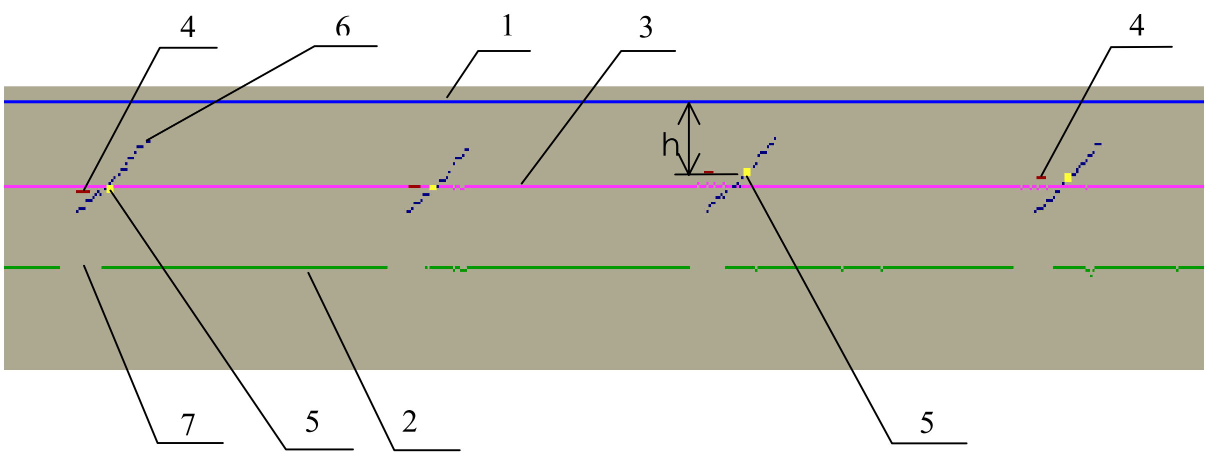


Figure 9. The schematic ultrasonic image (LB-scan).1 – front surface image; 2 – back surface image; 3 – simulated line of maximum valid incomplete penetration; 4 – image of a top of incomplete penetration for PEP1; 5 – image of a top of incomplete penetration for PEP2; 6 - curve composed of points corresponded to travel time of pulses (PEP2) reflected from the top penetration zone; 7 – image of shadow of incomplete penetration.

The image elements have different colors. The front surface (1) is shown in blue. The back surface (2) is shown in green. The level of the maximum valid incomplete penetration (3) is red. The top of incomplete penetration is dark red for the PEP1 (4) and yellow for the PEP2 (5). The curve (6) reconstructed by points corresponding to the travel time of pulses reflected from the top penetration zone is dark blue. The location of the line (3), imaging a technologic incomplete penetration, is obtained by the software after testing the standard sample with the defined depth of penetration. The minimum arrival time of the PEP2's signals, reflected from the top of incomplete penetration, is a parameter, processed by software to reconstruct the curve (6) composed of points corresponding to the travel time of pulses. As the minimum ultrasonic pulse propagation time t_{min} corresponds to the adjustment of an acoustic beam axis to a zone of the top of the incomplete penetration and as the reflected pulse amplitude is a maximum (the point (5) on the curve (6)), then $t_{min} = \varphi(h)$, where h is a depth of penetration. The weld is a defect, if the point (5) on the curve (6) or the line (4) is higher than a line (3), namely h is less than a permissible value. As the measurement of an incomplete penetration size is carried out by the pulse propagation time to a top of penetration, the estimation error of h does not depend on a reflected amplitude fluctuation. Besides the two-channel measurement of an incomplete penetration increases reliability in $\sqrt{2}$ times. The presence of the line (3) and the curve (6), not only simplifies the measurement of an incomplete penetration size, but increases an accuracy, if the image (4) of an incomplete penetration top is absent for the first channel (PEP1).

The ultrasonic introscopes operating at frequencies of 10–50 MHz with pulses 20–50 ns have been created. New methods for deriving ultrasonic images have been designed. These are the layer-by-layer scan (T-scan), the "sum" image of sections of the whole region test zone (LB-scan), the two-channel LB-scan. The size of defects detected with the help of ultrasonic images makes more than $\lambda/2$, where λ is a wavelength $\lambda \approx 0.12$ mm in metals at the frequency of 50 MHz.

The developed methods have to be applied to ultrasonic introscopes "IMIN–1S" and "IMIN–2S". This introscopes allow performing automatic tests of weld joints of different parts.

Literature

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