

## Selected Aspects of Ultrasonic Testing of Difficult Materials

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**Abstract:** Welding is considered as a “Special Process”, which means that its quality cannot be readily verified and its successful application requires specialist management, personnel and procedures. It is important to conduct proper testing of the welded joints, including volumetric testing. In this case there are conducted ultrasonic testing, which enable detecting volumetric discontinuities. Ultrasonic testing meets many problems while testing joints with large anisotropy. The problems are caused by the physical phenomena, e.g. transformation, dispersion and absorption of the wave. It is connected with the structure of the material, which cause different propagation of the ultrasonic beam. The article presents the review of the factors affecting the quality of ultrasonic testing.

**Keywords:** non-destructive testing, NDT, ultrasonic testing

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The making of machinery and elements of industrial equipment often necessitates the welding of materials characterised by significantly different physical properties. Dissimilar joints often find applications in power engineering equipment, chemical systems or reactors. For instance, in power boilers, heat exchange pipes exposed to very high temperature are made of austenitic steels and joined with system elements made of ferritic steels. Austenitic-ferritic steels and duplex steels are used in the production of chemical cargo carriers. Structural elements in joints with elements of containers made of duplex steels constitute dissimilar joints (e.g. with high-strength low-alloy steels). Ultrasonic tests of high-alloy steels, welding alloys having a significant nickel content and joints of dissimilar materials, e.g. low and high-alloy steels, and alloys having a high nickel content are usually more difficult than tests of ferritic welds.

Factors taken into account include, among other things, the chemical composition and the microstructure, the differences between which are presented below:

- Chemical composition
  - low-alloy steel
    - ▶ iron
    - ▶ + carbon <2%
    - ▶ + alloys <2%
  - duplex, stainless steel (304, 316, 321...)
    - ▶ iron
    - ▶ + carbon <2%
    - ▶ + alloys up to ~20% (primarily nickel and chromium)
- Microstructure
  - low-alloy steel
    - ▶ ferritic structure
  - stainless steel
    - ▶ ferritic structure
    - ▶ austenitic structure
    - ▶ ferritic/austenitic structure.

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mgr inż. Łukasz Rawicki (MSc Eng.), prof. dr. hab. inż. Jacek Słania (Professor PhD (DSc) Habilitated Eng.) – Łukasiewicz Research Network – Instytut Spawalnictwa

In terms of the weld, a problem encountered during the testing of materials characterised by high anisotropy is the coarse-grained structure (examples are presented in Figure 1). As crystals are oriented perpendicularly towards the gradient of temperature, the velocity of waves in the weld is different from that in the base material.

As a result, the weld material is anisotropic, heterogeneous and responsible for the high attenuation and scattering of waves; reflection is possible at the weld-base material interface. Problems present during tests include structural noise, quick wave attenuation, changes in the direction of wave propagation and the reflection of waves.

The testability of high-alloy steels, austenitic steels and joints of dissimilar materials should be determined in relation to each welding procedure, thickness and material grade. The performance of tests should be preceded by the collection of information concerned with the following aspects:

- velocity of ultrasonic waves in a test material and the weld transition zone,
- attenuation of ultrasonic waves,
- presence of false echoes connected with the material structure (grain size, segregation of alloying components).

Changes in the velocity of ultrasonic waves for steels and test materials necessitate related corrections when scaling the ultrasonic defectoscope. Tests performed using angle transducers should take into account changes of the refraction angle. The lack of refraction angle correction leads to the wrong location of discontinuities (Fig. 2). The testing of welds made of specific materials may necessitate the making of special transducers and reference specimens (Fig. 3).

Other important issues include heat treatment and the grain size in joints subjected to tests (see Figures 4 and 5 as well as Tables 1 and 2). In the anisotropic material, waves are scattered if the mean grain size amounts to  $0.1\lambda$ . The interfering scattering of waves takes place in relation

to a mean grain size of  $0.2\lambda$ . A grain diameter of  $0.5\lambda$  may indicate significant scattering potentially precluding the detection of very small discontinuities. It is not possible to test austenitic steels having a grain size of 0.8 mm when using the shear waves transducer having a frequency of 2 MHz. In turn, transducers having a

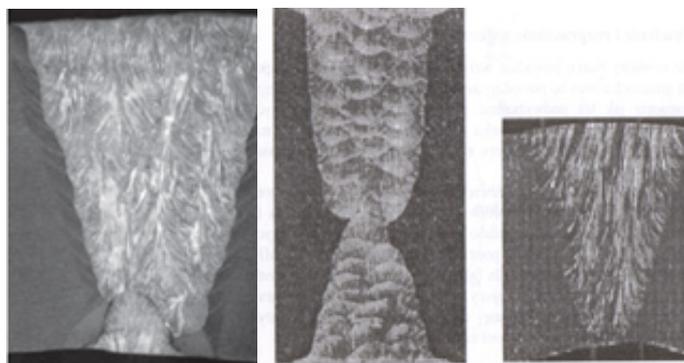


Fig.1 Coarse-grained structure

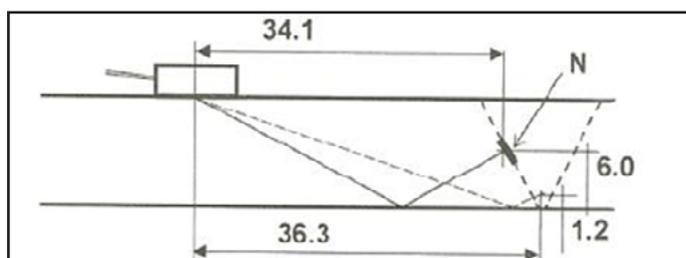


Fig. 2 Incorrect determination of material discontinuities resulting from the lack of transducer angle correction



Fig. 3 Examples of reference specimens with artificially made reference discontinuities

frequency of 4 MHz prove useless in relation to a grain size restricted within the range of 0.4 mm to 0.5 mm [1].

The permissible detectability of discontinuities in relation to a wavelength of  $0.2\lambda$  and a frequency of 2 MHz when using shear waves transducers indicate mean grain size  $d=4$  mm. In relation to shear waves and a frequency of 4 MHz, the grain size limit value is  $d=2$  mm [1,2]. In austenitic steels, the mean grain size is usually restricted within the range of 0.5 mm to 2 mm. Tests involving the use of classical shear waves transducers do not always produce positive results. The scattering of waves is the lower, the smaller the grain size in relation to wavelength. In cases of bigger grains it is necessary to increase wavelength [1].

### Adjustment of testing sensitivity

To determine the size of a given indication it is necessary to adjust the appropriate sensitivity of testing equipment. In relation to anisotropic materials, the DAC method is the only method making it possible to precisely determine the location of discontinuities, yet it requires the preparation of calibration standards for each batch of structures.

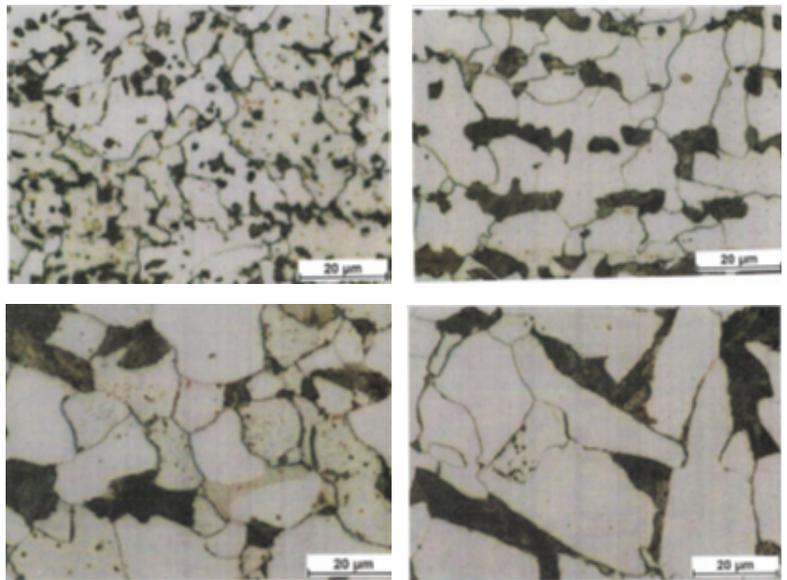


Fig. 4 Microstructure of ferritic steel S355J2 in the as-received state and after heat treatment

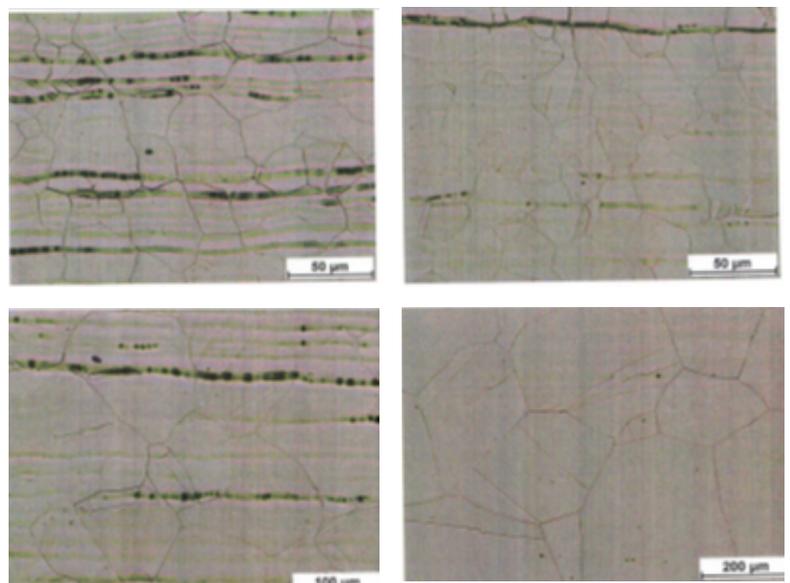


Fig. 5 Microstructure of austenitic steel X5CrNi18-10

Table 1. Designation of specimens including the content of ferrite and the grain size in relation to steel S355J2 [3]

Specimen designation	Ferrite content, %	Grain size, µm
1A	83	7.5
1B	84	7.7
1C	85	8.3
1D	83	10.0
1 A: as-received state 1 B: annealing at a temperature of 950°C; cooling along with the furnace 1 C: annealing at a temperature of 1100°C; cooling along with the furnace 1 D: annealing at a temperature of 1250°C; cooling along with the furnace		

Table 2. Designation of specimens and the grain size in relation to steel X5CrNi18-10 [3]

Specimen designation	Grain size, µm
2A	34.1
2B	27.1
2C	125.8
2D	206.9
2 A: as-received state 2 B: annealing at a temperature of 950°C; cooling along with the furnace 2 C: annealing at a temperature of 1100°C; cooling along with the furnace 2 D: annealing at a temperature of 1250°C; cooling along with the furnace	

The location of an indication on a display determines the distance between the indication and the transducer, whereas the height of the indication determines the size of the discontinuity. The DAC technique, also referred to as a comparative curve or a comparative line can be used in cases of materials characterised by strong attenuation triggered, among other things, by the coarse-grained structure of austenitic welds. The aforesaid technique is an experimental method enabling the determination of heights of echoes obtained from the same reflectors, located at different distances from the transducer [4]. The DAC technique-based testing takes into account the actual amplitude of signals related to the distance between a discontinuity and the transducer. An important advantage of the DAC method is the unnecessary of making allowances for transfer losses, as standards are made of the same materials as elements subjected to tests. A properly made standard is characterised by the following [4]:

- surface identical to that of the joint fragment subjected to tests,
- lack of mechanical and corrosion-induced surface damage, precluding the proper contact with the transducer,
- reference hole made perpendicularly to flat surfaces.

The drawing of a curve using the DAC technique consists of the following stages [ 4]:

- preparation of a reference specimen using a comparative reflector with a pass-through hole drilled perpendicularly to the direction of ultrasonic wave propagation,
- selection of an appropriate transducer and the adjustment of measurement parameters and observation range,
- testing equipment check (checking of a defectoscope, verification of testing parameters and the scaling of an observation range),
- testing a reference specimen aimed to identify the reflector providing the highest echo,
- adjusting the gain of defectoscopic equipment so that the highest echo reaches 80% of the

- entire height of the screen,
- designation of the position of echoes from the reference reflector; the amplitudes of the echoes should be restricted within the range of 20% to 80% of the screen,
- drawing a line through previously designated points from reference reflectors.

In accordance with the requirements specified in related materials and technical specifications, the selection of an ultrasonic technique related to joints made of austenitic steels, dissimilar materials or materials joined by means of nickel alloys should be performed using a representative reference specimen. The aforesaid specimen should contain a weld and be made using the same welding procedure as that applied when making the test joint. The aforesaid requirements should include the thickness of materials being joined as well as filler metals and base materials [7].

Reference reflectors have the form of discontinuities simulating indications expected in elements subjected to tests. If the aforesaid solution is not possible, it is necessary to use (cylindrical) side drilled holes (SDH) located in a representative specimen, in areas of expected discontinuities [8, 9]. The SDH diameter should be similar to the minimum size of a discontinuity to be detected and is usually restricted within the range of 2 mm to 5 mm. The selection of the minimum diameter of the standard reflector depends on test frequency. The diameter of reflectors in the form of pass-through holes increases along with decreasing test frequency. Usually, reflectors used for the adjustment of sensitivity are cylindrical transverse (side) holes having a diameter of 3 mm [10]. It is also possible to use flat-bottomed holes, spherical-bottomed holes or rectangular holes. As regards indications located near the surface, the most popular reflectors used when testing anisotropic materials are cylindrical pass-through holes or rectangular holes [11]. Exemplary locations of standard reflectors in test joints are presented in Figure 6 [11].

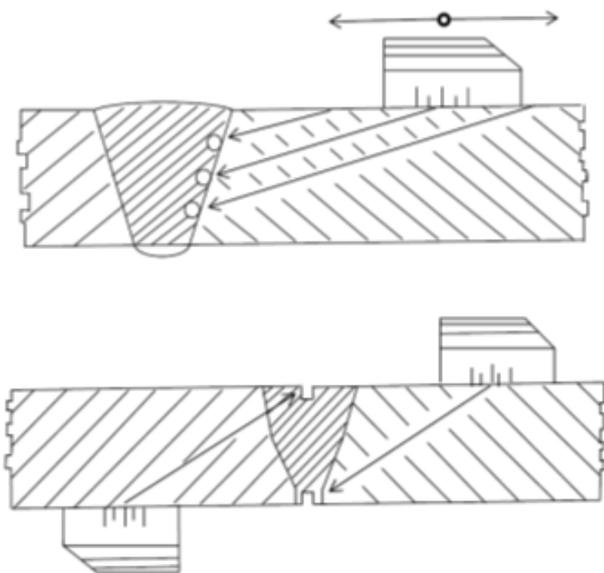


Fig. 6 Locations of reference reflectors in the weld:  
A) pass-through holes, B) rectangular holes [11]

Pass-through holes and rectangular holes are made in the fusion line of a welded joint and in the centre of the weld. The use of the groove as the standard reflector during tests involving the application of shear waves transducer is responsible for the double reflection of waves against the groove surface and the double separation of shear waves. Longitudinal waves lose significant power, leading to the lack of high echo from the rectangular groove. Because of this, the rectangular groove is not a recommended reflector as regards skew longitudinal waves [11].

The verification and making allowances for attenuation in tested joints of dissimilar materials requires the making of reference reflectors in relation to each material. Each test material is characterised by a different velocity of an ultrasonic wave, which necessitates the performance of separate tests in relation to each material. A specimen containing a representative weld should be made in a manner making it possible to properly identify the effect of weld material attenuation and enable the adjustment of appropriate test sensitivity. Modelling tools in the form of reference specimens are strongly recommended for adjusting the parameters of measurement transducers. The application of reference specimens reduces the risk of errors during tests, enables the optimisation of

parameters because of detectability based on ultrasonic waves or geometric limitations and verifies the usability of a given testing technique [8].

Reference specimens are used in the following areas [7]:

- test concerning the signal noise ratio (SNR) in the base material and in the weld,
- verification of the presence of echoes from apparent indications caused by reflection-related noise and changes of the beam in the fusion line or columnar crystallites,
- verification of the detectability of discontinuities and the manner of their assessment,
- selection of ultrasonic transducers for individual zones of the welded joint and bevel angles,
- development of test procedures,
- adjustment of test parameters.

In dissimilar joints, because of the variable anisotropy and the structural heterogeneity of individual joint areas, reference gain is a variable parameter. In relation to transducers used in the tests it is necessary to draw separate comparative curves and make allowances for attenuation resulting from the ultrasonic beam effect on the weld of a test material. The adjustment of test sensitivity and the identification of the level of gain belong to the most important aspects concerning the preparation of equipment for ultrasonic tests. The settings of test sensitivity affect the recording and assessment of indications obtained in ultrasonic tests [12]. Exemplary comparative curves are presented in Figure 7.

### Selection of transducers

The list of usable transducers:

- 45°, 60°, 70° shear wave
- transducers with a double element ADEPT
- LLT transducers
- mode conversion transducers
- “creeping wave” transducers

Figure 8 presents the qualification of a testing technique and the selection of an appropriate transducer

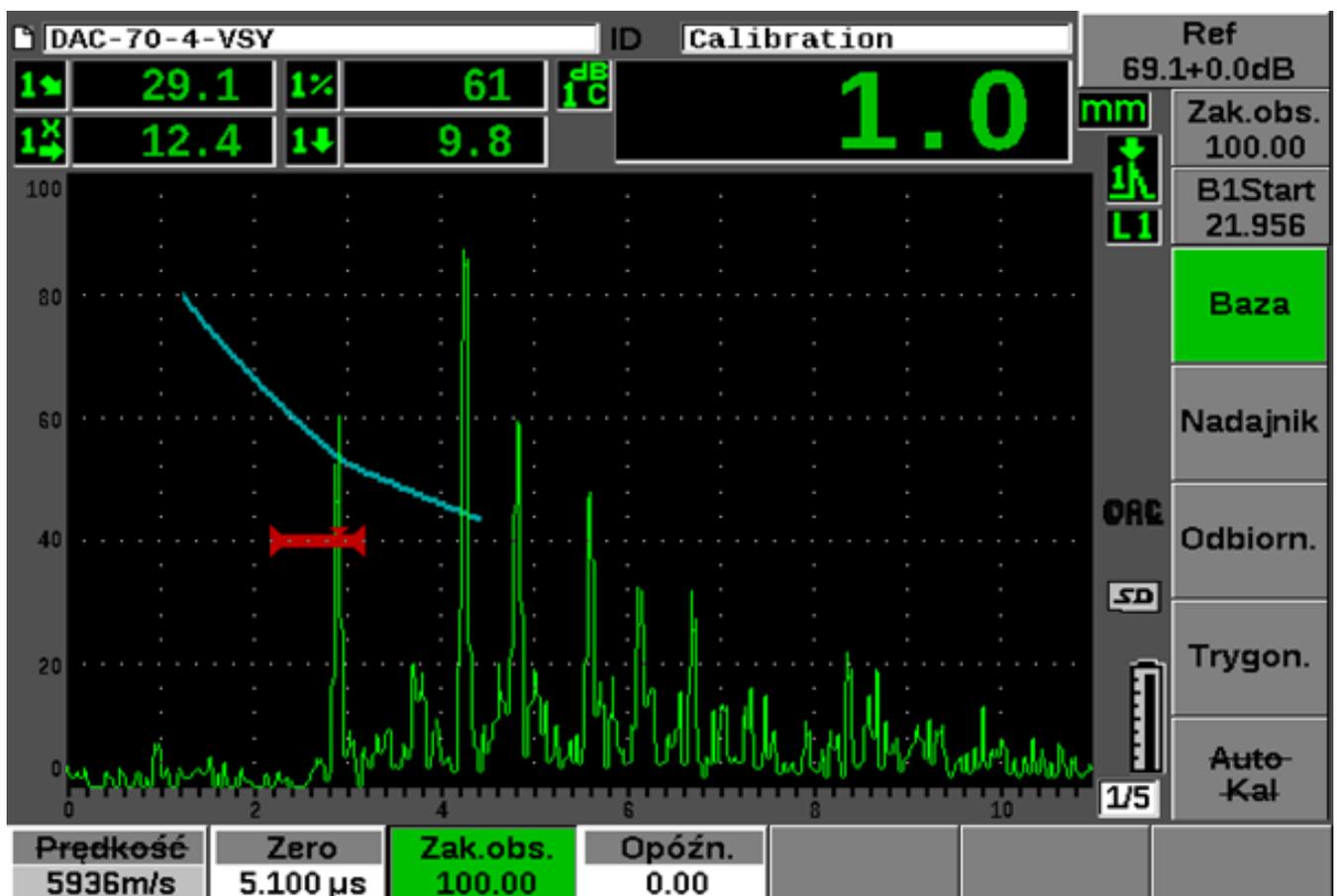
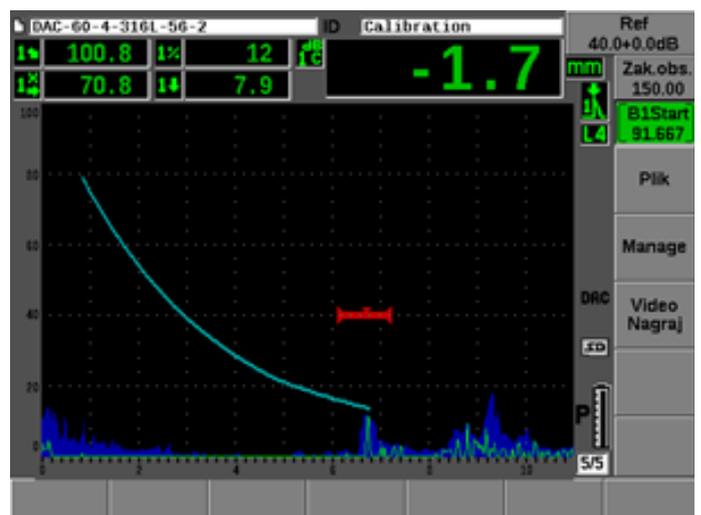
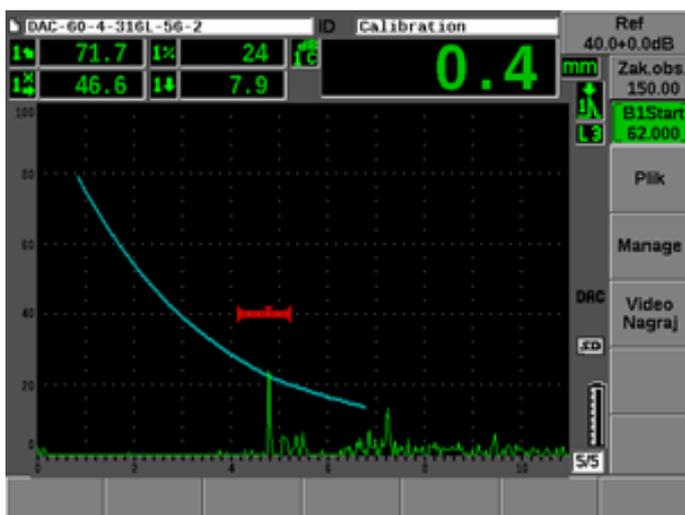
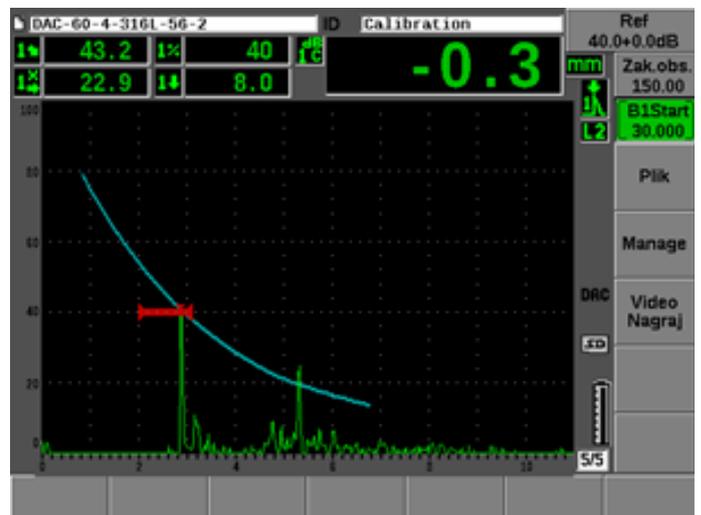
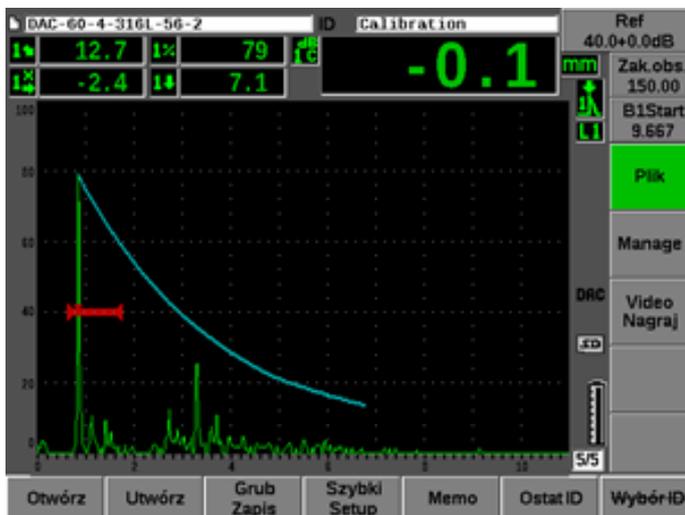


Fig. 7 DAC curve drawn using the shear wave and the longitudinal wave

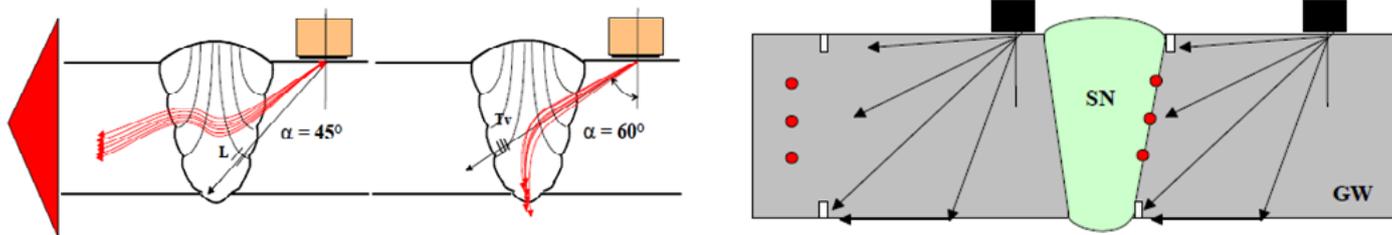


Fig. 8 Qualification of a testing technique and the selection of an appropriate transducer

The larger the sensitivity area, the higher sensitivity to the effect of noise-triggering grain boundaries. The signal-noise ratio can be improved by:

- limiting the sensitivity area,
- changing the beam divergence,
- change of impulse duration.

Tests involving the use of shear (transverse) waves of vertical polarity often trigger significant structural noise (see Figure 10).

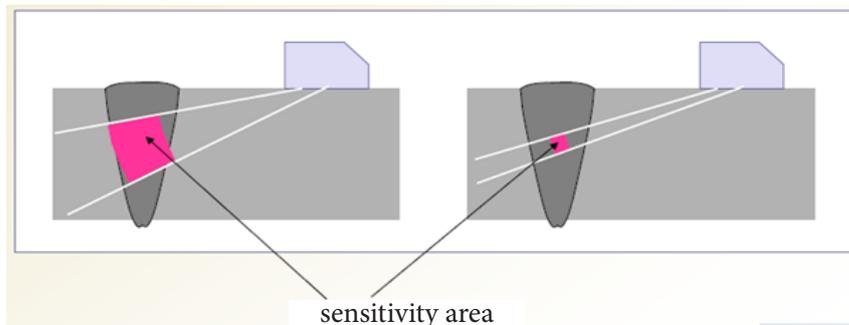


Fig. 9 Limitation of the sensitivity area during a test

### Application of modern ultrasonic techniques in non-destructive tests

The TOFD technique utilises the reflection and diffraction of ultrasonic waves on the edges of discontinuities in relation to the direction of waves [13,14]. In the TOFD technique, the orientation of a discontinuity in relation to the surface subjected to tests does not affect the detectability of the former. The method is used when testing technical structures in nuclear power engineering system as well as in the chemical and petrochemical industries. The TOFD technique involves the use of a transmitting transducer and a receiving transducer positioned opposite each other on a special bogie (on both sides of the weld) and working in the transmission mode [15]. The TOFD technique is characterised by very high accuracy, test speed and the very small number of false indications derived from discontinuities. As a result, it is possible to test welds, thicknesses of which are restricted within the range of 6 mm

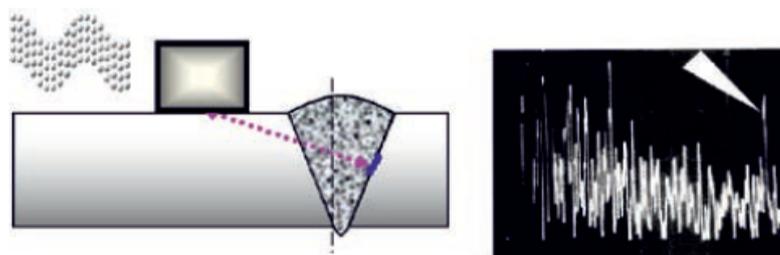


Fig. 10 Location and image of the indication of a discontinuity in the weld using the transverse vertical (VT) wave

to 300 mm [16]. Figure 11 presents the testing of fine-grained materials. Figure 12 presents the testing of a material characterised by high anisotropy.

The TOFD technique should not be used for the testing of coarse-grained materials. As can be seen in Figure 12, there are no signals from reference reflectors (SDH); only noise is recorded.

The Phased Array (PA) technique is based on ultrasonic phased-array transducers composed of 16, 32, 64 or 128 single transducers [17-19], each of which can independently emit and receive ultrasonic waves. The technique is used industrial applications to detect and estimate sizes of material discontinuities in various structures. Tests involving the use of the PA technique can be accompanied by noise derived from the interface between joined materials (see Figure 13).

Materials characterised by significant anisotropy and grain growth are tested using the TLR (Transmit-Receive Longitudinal) technique and a DMA (Dual Matrix Array) PA transducers. The technique utilises longitudinal waves and a sectoral scan, enabling the detection of indications located within the weld volume and near the opposite surface. Surface waves are used for detecting scanning surface-breaking indications and indications located directly under the surface. Figure 14 presents a test involving the use of the TLR technique.

Advantages resulting from the use of TLR transducers are the following:

- possible detection and sizing of indications generated by discontinuities located near the surface, within the volume of a welded joint and by the interface between the materials,
- improved detectability of discontinuities in coarse-grained materials and austenitic materials (difficult to test),
- improvement of the signal-noise ratio (SNR).

### Summary

In industrial conditions, particularly as regards elements of power generating equipment, reactors and chemical systems, it is necessary to make joints of steels characterised by different properties [20, 21]. Welding, belonging to special processes, does not offer ultimate certainty as whether a given joint has been made absolutely correctly. Because of the foregoing, it is necessary to perform non-destructive tests not

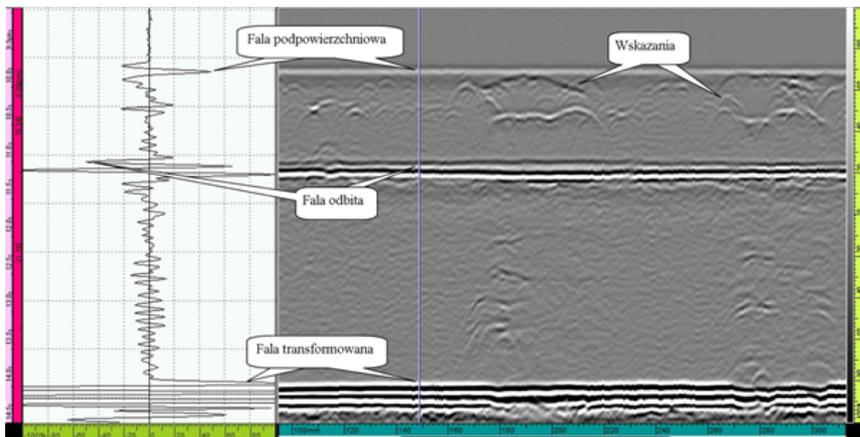


Fig. 11. TOFD technique – A-scan (diagram) and B-scan (TOFD image) during the testing of fine-grained steel

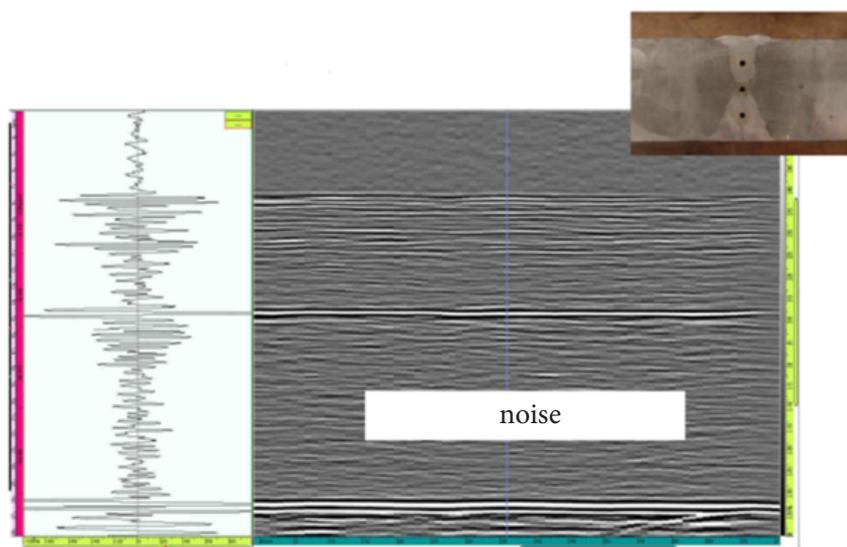


Fig.12. TOFD technique used in the testing of materials characterised by significant anisotropy

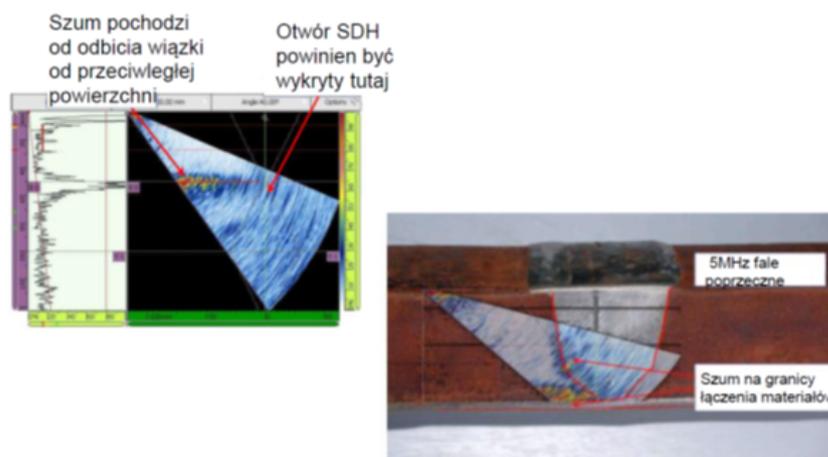


Fig13. Images obtained during PA technique-based tests in relation to materials characterised by different acoustic properties

affecting welded materials, and yet making it possible to assess the quality of the joint [22].

Ultrasonic techniques belong to non-destructive tests enabling the detection of volume

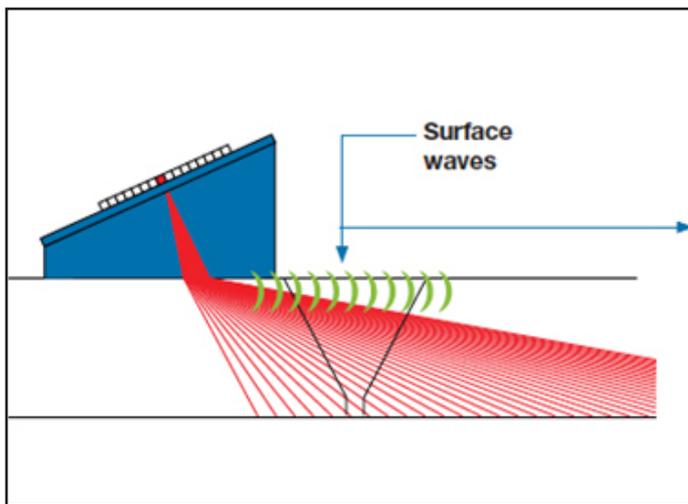


Fig. 14 TLR (Transmit-Receive Longitudinal) technique-based tests performed using DMA PA (Dual Matrix Array) transducers

discontinuities. Ultrasonic tests are accompanied by many difficulties when testing joints of dissimilar materials. The aforesaid difficulties result from physical phenomena such as the transformation and attenuation of waves. In addition, ultrasonic waves undergo refraction, reflection and, consequently, scattering [23]. The aforesaid unfavourable phenomena are connected with the material structure and result from differences in the propagation of ultrasonic beams. Because of the lack of fixed measurement conditions, parameters used in tests of welded joints are often adjusted experimentally.

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- Mgr inż. Łukasz Rawicki /MSc Eng./, prof. dr. hab. inż. Jacek Słania /Professor PhD (DSc) Habilitated Eng. – Sieć Badawcza Łukasiewicz /Łukasiewicz Research Network/ – Instytut Spawalnictwa